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# Photonics Radiation Effects Research Analysis

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13. ABSTRACT (*Maximum 200 words*)

This report presents the results of our analysis of nearly three hundred technical documents published or unpublished in the field of radiation effects in photonics. Previous research efforts on radiation effects in photonic components and systems were identified. The collected data was analyzed and an assessment was made as to the level of confidence of the data and the current knowledge of radiation effects testing. The conclusions provide a summary of the analysis and an appraisal of the suitability for use in a radiation environment of each element identified.

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## SUMMARY

To understand and characterize the effects of ionizing radiation in photonic components, research must begin with the historical documentation of and knowledge gained from past research efforts. The basic objective of this photonics radiation effects research analysis effort is to ascertain what effects were generated by the test conditions and what effects contributed to changes in the performance of a device under test. A clear understanding of all the parameters which affect the results is mandatory to obtain the ultimate objective of assessing radiation effects in photonic components and systems.

Commercial facilities, military laboratories, institutional organizations and government agencies within the United States and abroad have placed emphasis on the development of photonic devices that support optical computing, guidance and advanced switching capabilities. The evolution of a photonics radiation effects data base is evidenced by recent publications on: integrated optic (IO) devices, acousto-optic (AO) modulators, spatial light modulators (SLM), electro optic (EO) modulators, quantum well lasers, charged-coupled devices (CCD), and detector arrays. Other devices that are currently under investigation include: Bragg gratings, and non linear optical polymers, which are being evaluated to support the development of optical neural networks, optical correlators, optical expert systems, and synthetic aperture arrays as well as fiber optic data bus and digital wideband transmission networks. The terrestrial application of photonics technology for solving nuclear or hazardous waste monitoring are examples wherein both radiation hardening as well as radiation sensitivity is required.

Several criteria were established to evaluate the test results contained in our collected documents. Not only is it important to judge the relevance of the test data based on the personnel performing the work or the agency that undertook the testing, but it is also important to evaluate the test data based on the test facilities, test conditions, and limitations of the experiment. The parameters that were established to evaluate the test data within our collected documents, include the general elements of the report such as author and sponsor as well as when the test was conducted, and the test conditions were evaluated. The test parameters for each component which was tested in a given environment were also analyzed.

In order to assess the results of our findings during this analysis effort, it was necessary to provide an initial assessment of the associated damage mechanisms for the various photonic components under review. We divided the component and devices into six basic categories. The active transmission devices such as the light emitting diodes and lasers are in the first two classes that we established. Even though they are typically classified as sources in most publications, it was important for us to keep them separate since there are different radiation effects occurring in these devices. The passive branching devices such as couplers and connectors are listed as one category class. The connectors contain lenses, filters, indexing matching fluids, etc. The couplers contain beam splitters, waveplates, etc. All of theses passive elements are addressed in this category. Fibers which are predominantly the most tested components and provide the most complete set of test data are discussed the least in this report. For analysis purposes, we have included this information to demonstrate what is needed to eliminate many of the deficiencies that exist in the other device/environment categories. The integrated optic modulators and other active switching devices have the least amount of test data, but are addressed in detail in this report. These devices are the focus of this report as well as other new and innovative components. IO devices are such an important class of components that we divided this section in several subsections. Since we did not have the supporting test data to validate our results, we have included some theoretical assessments of these devices. The final category for our assessment and analysis effort includes all detectors. Broadband as well as point source detectors are incorporated in this category.

Significant progress has been made in identifying, delineating and standardizing radiation induced effects in optical fibers and components. To a much lesser extent, radiation induced effects in integrated optic guided wave structures have recently been the focus of a highly coordinated international round robin investigation. The AFMC Phillips Laboratory has supported the DNA photonics program by investigating and reporting the results of radiation induced effects in passive and active SLM , IO and AO devices. These first results, and the confirmation and new findings of other experimenters, indicate that the responses of many photonic devices, both dated and new, are largely unknown and require continued and coordinated study to address and support space, nuclear weapons and environmental requirements and applications. Application of the photonics

radiation effects and hardening data base is transitioning to the space environment or to addressing nuclear waste and contamination concerns. Highly coordinated research is required to compensate for the decrease in traditional funding appropriated towards radiation effects research. While the funding allocations towards this end have dwindled, the requirement for hardening technology may be greater than ever.

## PREFACE

The authors are indebted to Charles E. Barnes of JPL for his extensive, valuable information on radiation damage mechanisms in photonic components, subsystems and systems which has been integrated into this report. Dr. Barnes provided extensive information on various types of optical modulators.

CONVERSION TABLE

Conversion factors for U. S. Customary to metric (SI) units of measurement

MULTIPLY ————————————→ BY ————————————→ TO GET
TO GET ————————————→ BY ————————————→ DIVIDE

| | | | |
|---|---|---|---|
| angstrom | 1.000 000 | XE -10 | meters (m) |
| British thermal unit (thermochemical) | 1.054 350 | XE+3 | joule (J) |
| calorie (thermochemical) | 4.184 000 | | joule (J) |
| cal (thermochemical)/cm$^2$ | 4.184 000 | XE-2 | mega joule/m$^2$ (MJ/m$^2$) |
| curie | 3.700 000 | XE+1 | *giga becquerel (GBq) |
| degree Fahrenheit | $T_K$=(T°F+ 459.67)/1.8 | degree kelvin (K) | |
| electron volt | 1.602 19 X E-19 | joule (J) | |
| erg | 1.000 000 | XE-7 | joule (J) |
| erg/second | 1.000 000 | XE-7 | watt (W) |
| foot-pound-force | 1.355 818 | | joule (J) |
| inch | 2.540 000 | XE-2 | meter (m) |
| jerk | 1.000 000 | XE+9 | joule (J) |
| joule/kilogram (J/kg) (radiation dose absorbed) | 1.000 000 | | Gray ('Gy) |
| kip (1000 lbf) | 4.448 222 | XE+3 | newton (N) |
| kip/inch$^2$ (ksi) | 6.894 757 | XE+3 | kilo pascal (kPa) |
| ktap | 1.000 000 | XE+2 | newton-second/m$^2$ (N-s/m$^2$) |
| micron | 1.000 000 | XE-6 | meter (m) |
| mil | 2.540 000 | XE-5 | metet (m) |
| pound-force (lbs avoirdupois) | 4.448 222 | | newton (N) |
| pound-force inch | 1.129 848 | XE-1 | newton/meter (N◊m) |
| pound-force/inch | 1.751 268 | XE+2 | newton-meter (N/m) |
| pound-force/foot$^2$ | 4.788 026 | XE-2 | kilo pascal (kPa) |
| pound-force/inch$^2$ (psi) | 6.894 757 | | kilo pascal (kPa) |
| rad (radiation dose absorbed) | 1.000 000 | XE-2 | **Gray (Gy) |
| roentgen | 2.579 760 | XE-4 | coulomb/kilogram (C/kg) |

* The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

** The Gray (GY) is the SI unit of absorbed radiation.

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# SECTION 1

## INTRODUCTION

In the early 1970's researchers began an extensive radiation test program in fiber optics. The primary focus of these test programs was on optical fibers and initial findings demonstrated permanent induced absorption in these components. As advances in material composition improved the bandwidth, changed the operating wavelength and increased throughput speeds of optical fibers, their performance in ionizing radiation environments also improved. In the 1980's as environmental parameters changed and new electro-optic systems evolved, a greater emphasis in testing of the active components progressed. More emphasis was placed on active components to include the sources and detectors as well as interferometric components for sensor systems. These components were found to be susceptible to transient radiation effects and experienced permanent damage from neutron fluence levels. Today researchers at numerous government, institutional and commercial facilities have initiated a series of coordinated studies and experimental investigations to identify, delineate and isolate radiation-induced effects in photonics. This recent emphasis has shifted to charge coupled devices (CCDs), integrated optic (IO) structures, acousto-optic (AO) modulators and spatial light modulators (SLMs). Motivation for this recent emphasis has been the commercial and military advocacy of these technologies in a wide variety of applications including optical signal processing, smart sensors and other applications such as space systems where increased bandwidth, reduced weight, reduced size and lowered energy consumption are important[1-8].

To understand and characterize the effects of ionizing radiation in photonic components, research must begin with the historical documentation of and knowledge gained from past research efforts. The basic objective of this photonics radiation effects research analysis effort is to ascertain what effects were generated by the test conditions and what effects contributed to changes in the performance of the device under test. A clear understanding of all the parameters which affect the results is mandatory to obtain the ultimate objective of assessing radiation effects in photonic components and systems.

# SECTION 2

## RESEARCH ANALYSIS

Commercial facilities, military laboratories, institutional organizations and government agencies within the United States and abroad have placed emphasis on the development of photonic devices that support optical computing, guidance and advanced switching capabilities. As evidenced in recent International Society for Optical Engineering Conferences, "Photonics for Space Environment Conferences I - II "[3, 4] and other contemporary technical conferences in Europe [5,6] and in the United States, [7,8] there is both a great appeal and requirement for space and terrestrial hardened photonic technologies. The evolution of a photonics radiation effects data base resulting from these conferences and earlier international studies is evidenced by publications on: integrated optic (IO) devices, acousto-optic (AO) modulators, electro optic (EO) modulators, quantum well lasers, charged-coupled devices (CCD), and detector arrays. Other devices that are currently under investigation include: Bragg gratings, and non linear optical polymers, which are being evaluated to support the development of optical neural networks, optical correlators, optical expert systems, and synthetic aperture arrays as well as fiber optic data bus and digital wideband transmission networks. The terrestrial application of photonics technology for solving nuclear or hazardous waste monitoring are examples wherein both radiation hardening as well as radiation sensitivity is required. Technical papers presented at conferences in the United States have also emphasized research regarding radiation damage to porous sol-gel glasses[9], optical couplers[10], light emitting diodes (LED)[11], spectroscopic instruments[12], HgCdTe arrays[13], and Si microvolumes[14]. Recent European papers have reported radiation induced effects observed in polymer clad silica (PCS) optical fiber sensors (Croatia)[15], fiber Bragg grating sensors (France)[16], fluorine doped fibers (Russia)[17], all silica fibers (Czech Republic)[18], passive and active optical components (Germany)[19-20], and imaging optics (Japan)[21].

The largest accumulation of correlated radiation induced effects testing on IO and fiber optic, photonic components has been generated by the Air Force Material Command (AFMC) Phillips Laboratory in Albuquerque, New Mexico and member organizations of the Tri-Service Fiber Optic - Photonics Coordinating Committee and the NATO Panel IV, Research Study Group 12 - Nuclear Effects Task Group (NETG). Individual and round-robin international experimental studies have been performed on a regular basis for several of optical modulator technologies for the past four years. The NATO NETG has also performed steady state and transient radiation tests on passive integrated optic couplers. Most of the radiation testing has been performed on optical fibers as well as other passive optical components. There has been very little system testing as is evidenced by our lack of collected documents or contacts with professional organizations and personnel.

## 2.1 COLLECTION AND IDENTIFICATION OF INFORMATION.

In order to establish a basis for this research effort a few bounds and constraints were identified. Limited data was collected since most of the development and fabrication of photonic components such as optical sources, optical modulators, passive optical elements and detectors were only basic research concepts prior to 1980. Fibers were included in our analysis because of their integral importance to photonic systems as well as the evolution of these materials to include polarization maintaining fibers and erbium doped fiber amplifiers (EDFA).

With our current access to numerous technical publications, participation in various test programs, and attendance at diverse conferences, we were able to collect nearly 300 technical documents of photonics radiation effects testing, a number of which were unpublished. These documents are listed in Appendix A by author, title, and date. Table 2-1 provides a distribution of the information contained in the 281 documents and is shown in a matrix format. The key components of a photonic system are listed on the vertical side of the matrix, and the nuclear radiation environments are listed in the horizontal direction. Each cell of the matrix contains the number of reported test results that were identified for a given device in a defined environment. Since some documents contained multiple tests of different components and/or different environments, the total numbers are greater than the number of documents collected.

Table 2-1. Distribution of documents.

| Element of Fiber Optic System | Nuclear Radiation Type: Total Dose | Prompt Transient | Proton Fluence | Neutron Fluence | Total |
|---|---|---|---|---|---|
| LED | 21 | 9 | 12 | 20 | 62 |
| Laser Diodes | 17 | 10 | 9 | 15 | 51 |
| Couplers / Connectors | 14 | 10 | 8 | 3 | 35 |
| IO Device / Modulator | 9 | 11 | 2 | 2 | 24 |
| Optical Fiber | 142 | 55 | 21 | 13 | 231 |
| Photodiode / Detector | 29 | 18 | 19 | 19 | 85 |
| Total | 232 | 113 | 71 | 72 | |

Note: 281 documents have been incorporated into the database, wherein multiple components/environments exist.

## 2.2 SOURCES OF INFORMATION.

Personnel contacts were the most important resources that we utilized during our collection of the 281 test documents. We utilized our correspondence and involvement in the NATO Nuclear Effects Task Group, the DNA Radiation Hardness Assurance Photonics Working Group, the ASTM E13.09 Fiber Optic Spectroscopy Committee, the Nuclear Space Radiation Effects Conferences, the European Space and Radiation Effects Conferences, and the Society for Photo-optical Instrumentation Engineers Conferences to acquire the above listed documents. A list of some of the most frequent contributors is provided in Table 2-2. They are separated into two categories, national and international.

Table 2-2. Recognized professional radiation effects personnel and their affiliation.

| National | International |
|---|---|
| Firebele, NRL | Henschel, FINT |
| Taylor, Phillips Lab | West, RMCS |
| Barnes, JPL | Schneider, MBB |
| Greenwell, SEA | Johan, Gramat |
| Lyons, LANL | Hopkins, SIRA |
| Marshall, SFA | Hopkinson, SIRA |
| Looney, LANL | Adams, ESA |
| Scott, Aerospace | Dianov, CIS |
| Dale, NRL | Tanaka, Mitsubishi |
| LaBel, GSFC | Decreton, SCK/CEN |
| Evans, Boeing | Mashinsky, CIS |
| Smith, LLNL | Obara, JAERI |

Other individuals have also provided significant technical information, but their contributions were limited to only a few technical documents as compared to those listed above.

Figure 2-1 provides a graphical depiction of the authors' affiliation and summarizes the number of technical data points provided by the various organizations. In the United States, the majority of the test results were provided by DOE and DOD organizations. The foreign data contribution was predominantly gleaned from the NATO community. These results also represent the fact that most of the technical publications and organizations are supported by the DOD/DOE and NATO communities.

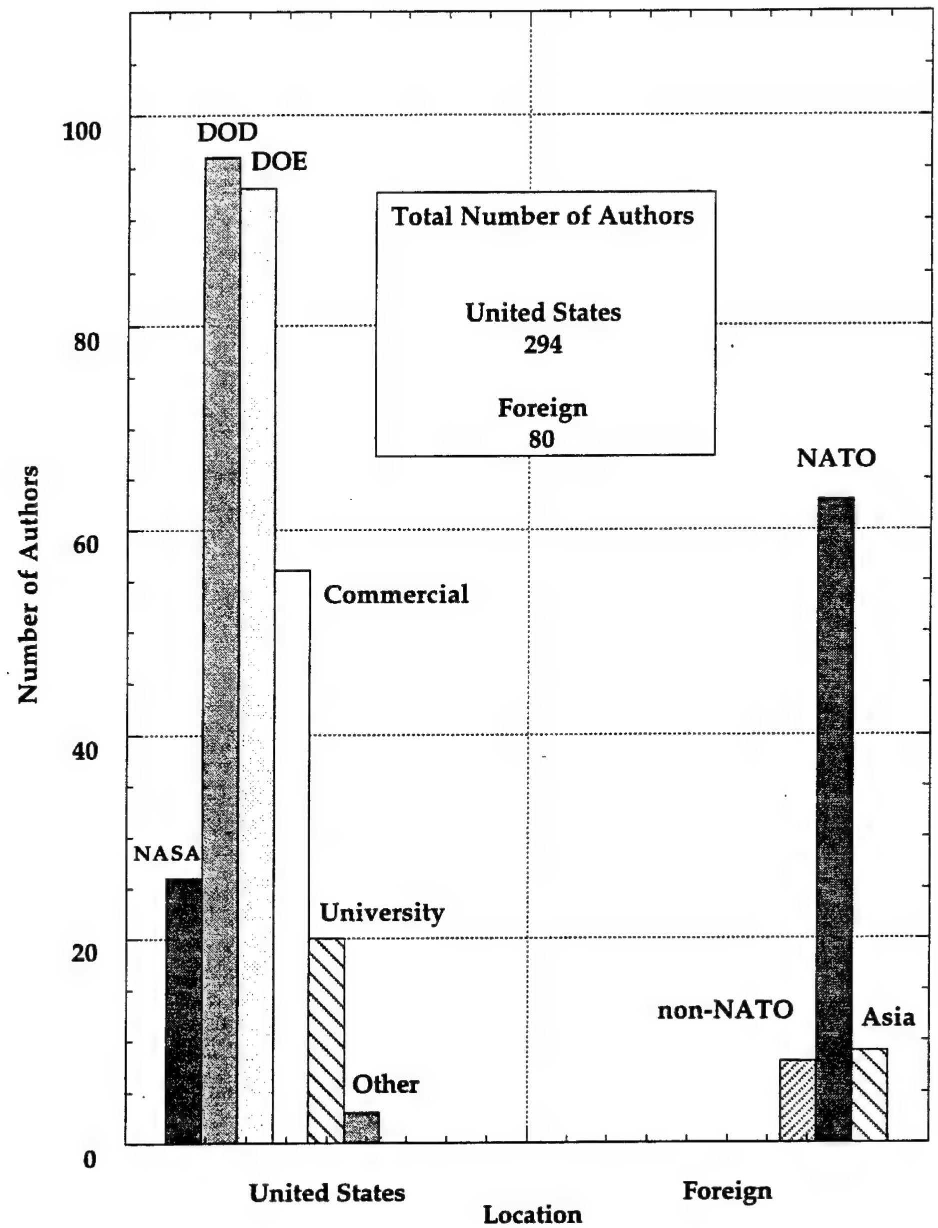


Figure 2-1. Author affiliation and the number of technical reports from each organization.

## 2.3 DOCUMENT EVALUATION PARAMETERS.

Several criteria were established to evaluate the test results contained in each document. Not only is it important to judge the relevance of the test data based on the personnel performing the work or the agency that undertook the testing, but it is also important to evaluate the test data based on the test facilities, test conditions, and limitations of the experiment. The parameters that were established to evaluate the test data within a particular document, include the general elements of the report such as author and sponsor as well as when the test was conducted, but the test parameters were also evaluated. The test parameters for each component which was tested in a given environment were analyzed. The minimum, maximum and typical values were listed (see Appendix B) for the appropriate test. Where extreme values were listed and there was no other facility that performed the test or comparable parameters from other tests, then the results were listed as inadequate. If only a few laboratories performed a test on a given device and there was no collaboration, then the test results were considered incomplete. Table 2-3 provides a status summary of the quality of the test data as it relates to each category of device tested for each environment. The neutron and proton categories are low because there exists no reported test results or at least the limited number of test results reported in these environmental categories cannot be collaborated. This is also true for the IO modulators as well as the coupler/connector components. There exists very little documented test data for these components. On the other hand, there is a lot of documented test data for optical fibers, and there is also consistent agreement between various laboratories and government (US and Foreign) facilities. The active sources and detectors also have good quality test results with some agreement between test facilities. These results will be analyzed in Section 3 of this report.

Table 2-3. Quality of prior test results.

| | Total Dose | Prompt Transient | Proton Fluence | Neutron Fluence |
|---|---|---|---|---|
| LED | M | M | L | L |
| Laser Diodes | M | M | L | L |
| Couplers / Connectors | L | L | L | L |
| IO Device / Modulator | L | L | L | L |
| Optical Fiber | H | H | L | L |
| Photodiode / Detector | M | M | L | L |

L - Incomplete
M - Adequate
H - Good

## SECTION 3

## RESULTS

In order to assess the results of our findings during this analysis effort, it is necessary to provide an initial assessment of the associated damage mechanisms for the various photonic components under review. We have divided the component and devices into six basic categories. The active transmission devices such as the light emitting diodes and lasers are the first two classes that we established. Even though they are typically classified as sources in most publications, it was important for us to keep them separate since there are different radiation effects occurring in these devices. The passive branching devices such as couplers and connectors are listed as one category class. The connectors contain lenses, filters, indexing matching fluids, etc. The couplers contain beam splitters, waveplates, etc. All of theses passive elements are addressed in this category. Fibers which are predominantly the most tested components and provide the most complete set of test data will be discussed the least in this report. For analysis purposes, we have included this information to demonstrate what is needed to eliminate many of the deficiencies that exist in the other device/environment categories. The integrated optic modulators and other active switching devices have the least amount of test data, but will be addressed in detail in this report. These devices are the focus of this report as well as other new and innovative components. IO devices are such an important class of components that we divided this section in several subsections. Since we did not have the supporting test data to validate our results, we have included some theoretical assessments of these devices. The final category for our assessment and analysis effort includes all detectors. Broadband as well as point source detectors are incorporated in this category. All of these components are discussed in the following sections.

### 3.1 DOCUMENTED RESEARCH STATUS.

In our analysis we observed an interesting transition in the types of testing undertaken over a period of ten years with some preliminary findings as early as 1975. In general the number of tests of photonic components in all radiation environments increased in the past five years. All the technical documents that were accessed for this research effort were published after 1975. Approximately one-third of the papers were published prior to 1990. Figure 3-1 demonstrates the distribution of documents collected by year for the past ten years plus the few years prior to 1984. All documents prior to 1984 were listed in one category. That year, 1984, was chosen as a starting point since it is a baseline for current test practices and standard test procedures. Most of the documents were published between January 1992 and December 1993, and address all test environments. A breakdown of this information in shown in Figure 3-2. All radiation testing during this time period are separated into specific environment categories to include total dose testing, prompt transient (x-ray and electron pulse) testing, proton testing, and neutron

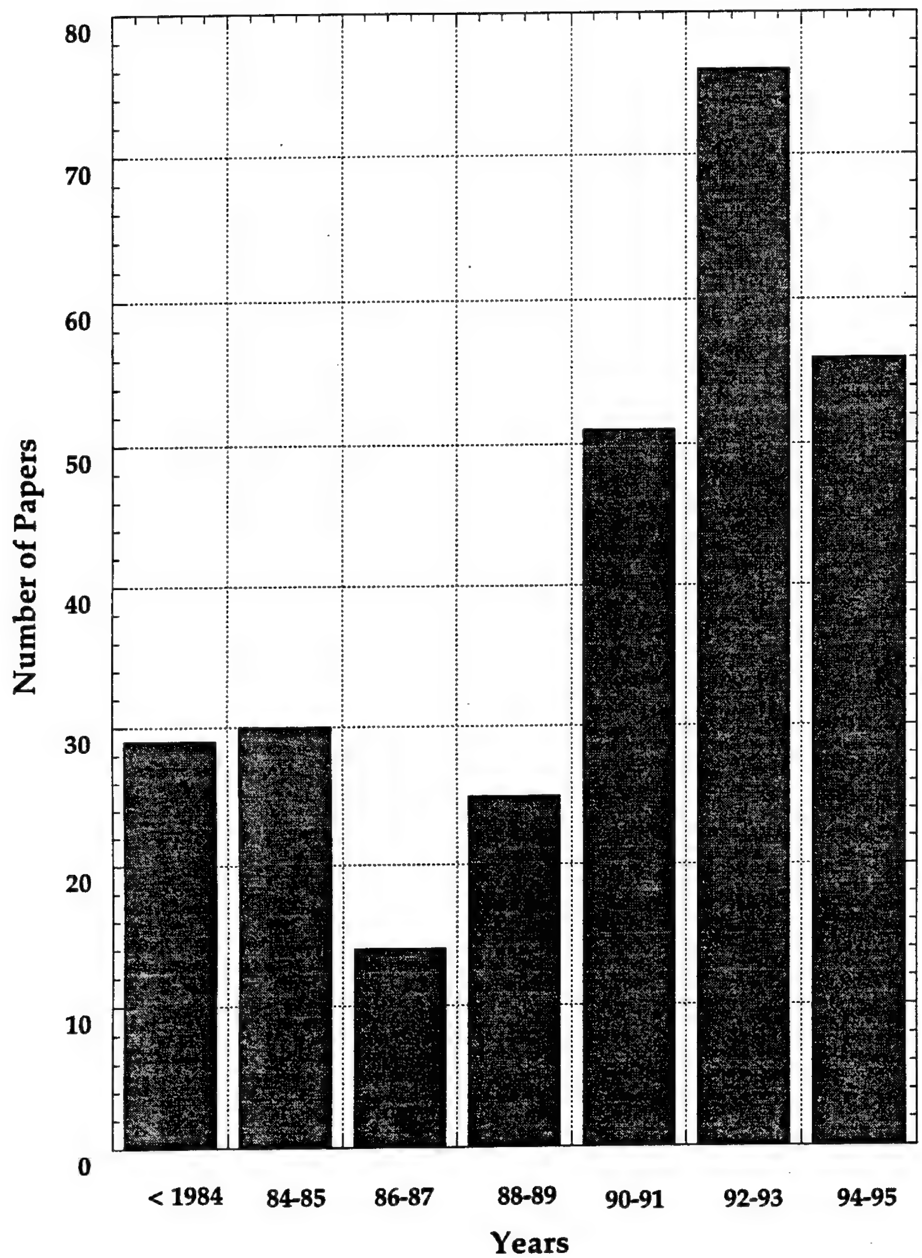


Figure 3-1. Number of papers over time for all radiation environments and devices.

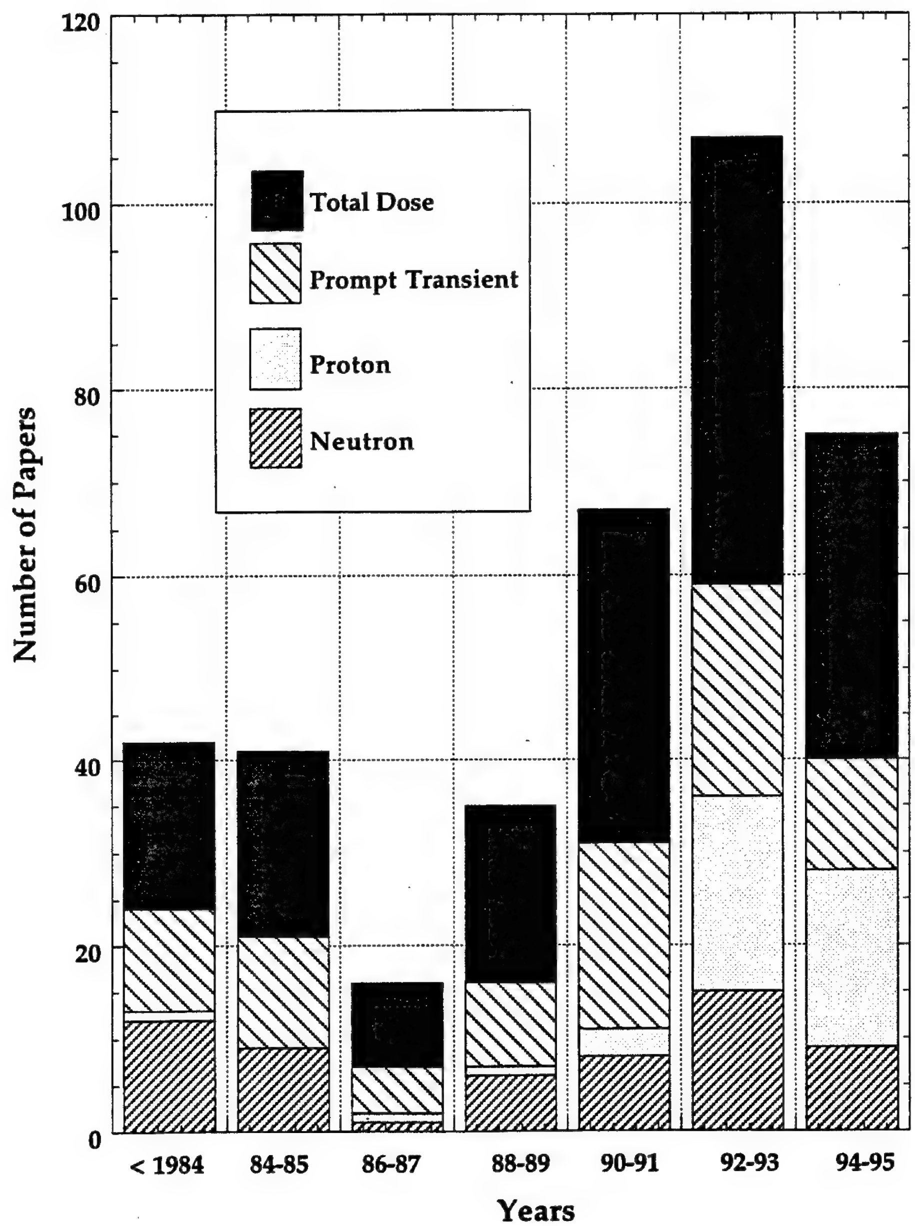


Figure 3-2. Number of papers over time for each radiation environment for all devices.

fluence testing. Prior to 1989, there was very little proton testing and some neutron testing prior to 1985. Most of the documents reported neutron and proton testing in more recent years since 1992. As shown in this chart, the predominant test environment is total dose testing. This is a typical test environment since it addresses most systems requirements for space environments, nuclear weapons environments, nuclear power plant environments, and nuclear waste storage environments. It also adheres to current test practices for microelectronics components. Figures 3-3 to 3-6 give a detailed distribution of the technical papers by specific environment that were accumulated for this study. Figure 3-3 shows the distribution of papers over time for all devices that were tested in a total dose environment. Nearly 50 devices were tested in the total dose environment from January 1992 to December 1993. That period alone equals the number of devices that were tested prior to December 1987. Most of the devices that were tested prior to 1987 were optical fibers, but during the 1992-1993 time period a variety of devices were tested to include IO, LED, laser, and photodiode components. Figure 3-4 depicts the time period for all devices that were tested in a prompt transient environment. Figure 3-5 shows the proton test distribution. Little to no testing occurred prior to January 1990. In the past four years, a number of active and passive devices have been tested to include couplers, IO modulators, sources and detectors. Figure 3-6 also shows similar results for neutron testing. Very little testing occurred prior to 1990 except for some LED, laser and photodiode testing at Sandia National Labs. prior to January 1985. More discussions and a more detailed breakdown of the results will be provided for each component classification.

Since most of the photonic component applications have been oriented to data transmission systems, it is apparent from Figure 3-7 that the largest number of data points exist around the transmission wavelengths of interest at 850 nanometers (nm), 1300 nm, and 1550 nm. The distribution also shows that most of the technology has been based on silica fibers with very little interest in the fluoride glass and chalcogenide glass fibers. Prior to January 1990, testing at 850 nm dominated research efforts. After 1990, testing at 1300 nm took precedence and there became a growing interest in testing at 1550 nm as well. This information is contained in Figure 3-8, which shows the transition from tests performed at 850 nm to tests performed at 1300 nm. However, it is also important to note that 850 nm wavelength tests have continued even with the evolution of the telecommunications industry to progress to longer wavelengths. More detail will be provided in the following sections of this report.

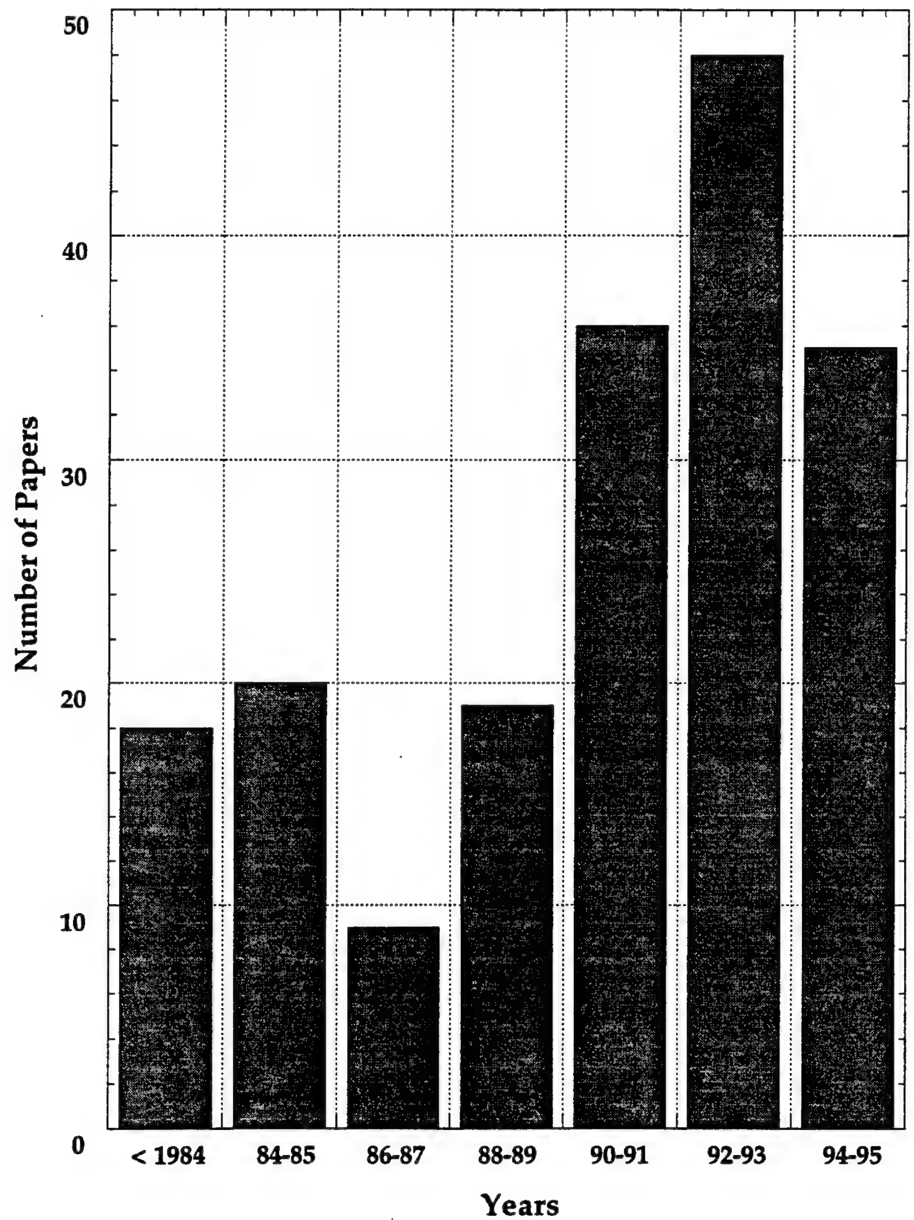


Figure 3-3. Number of papers over time for all devices in a total dose radiation environment.

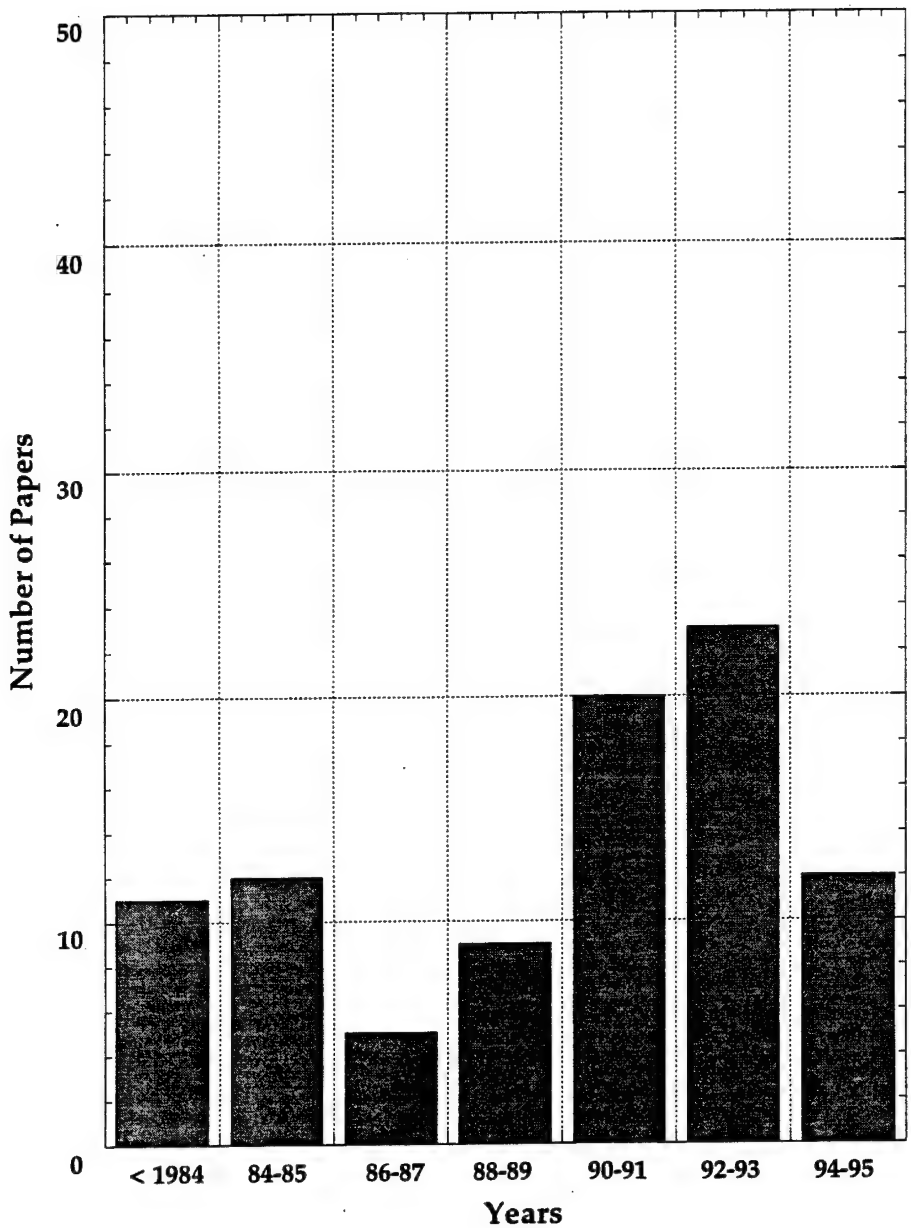


Figure 3-4. Number of papers over time for all devices in a prompt transient radiation environment.

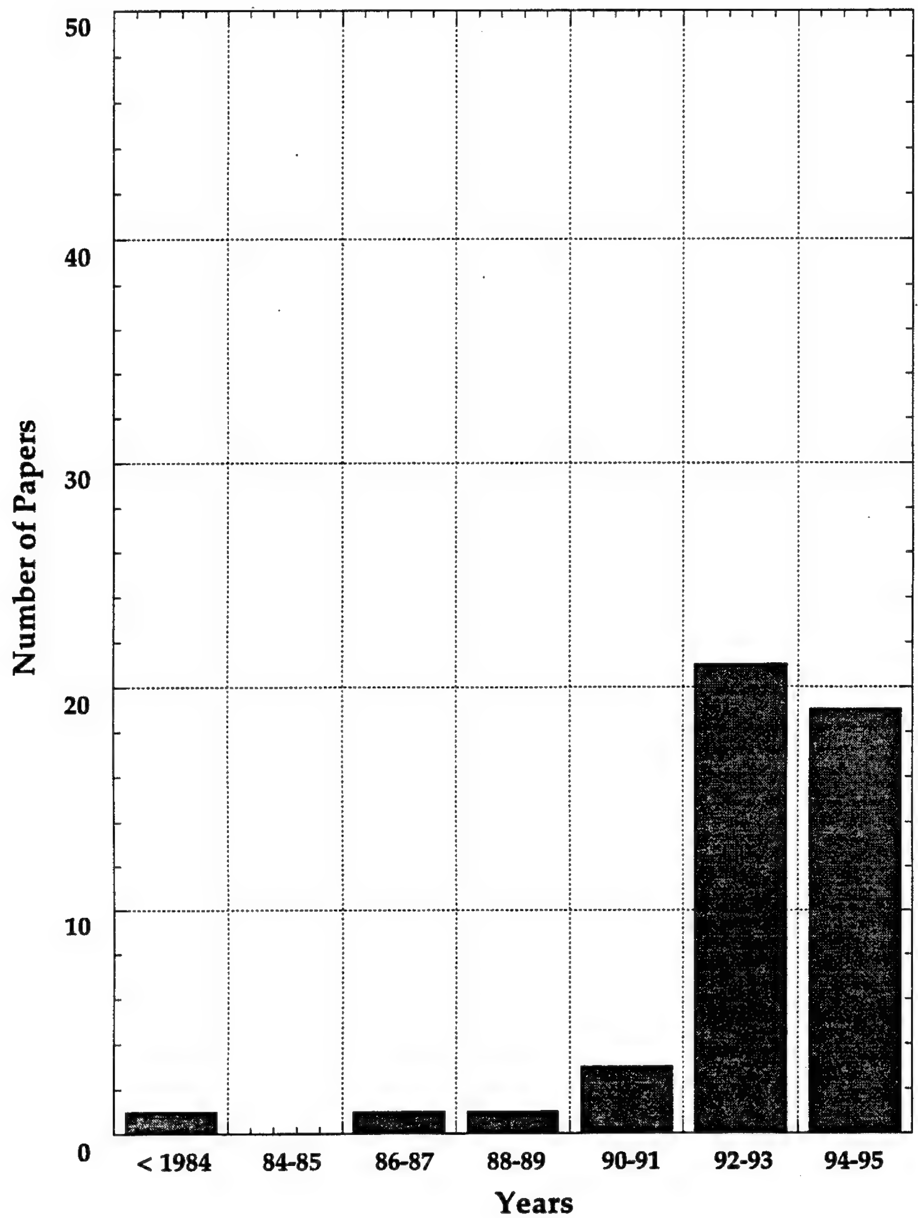


Figure 3-5. Number of papers over time for all devices in a proton radiation environment.

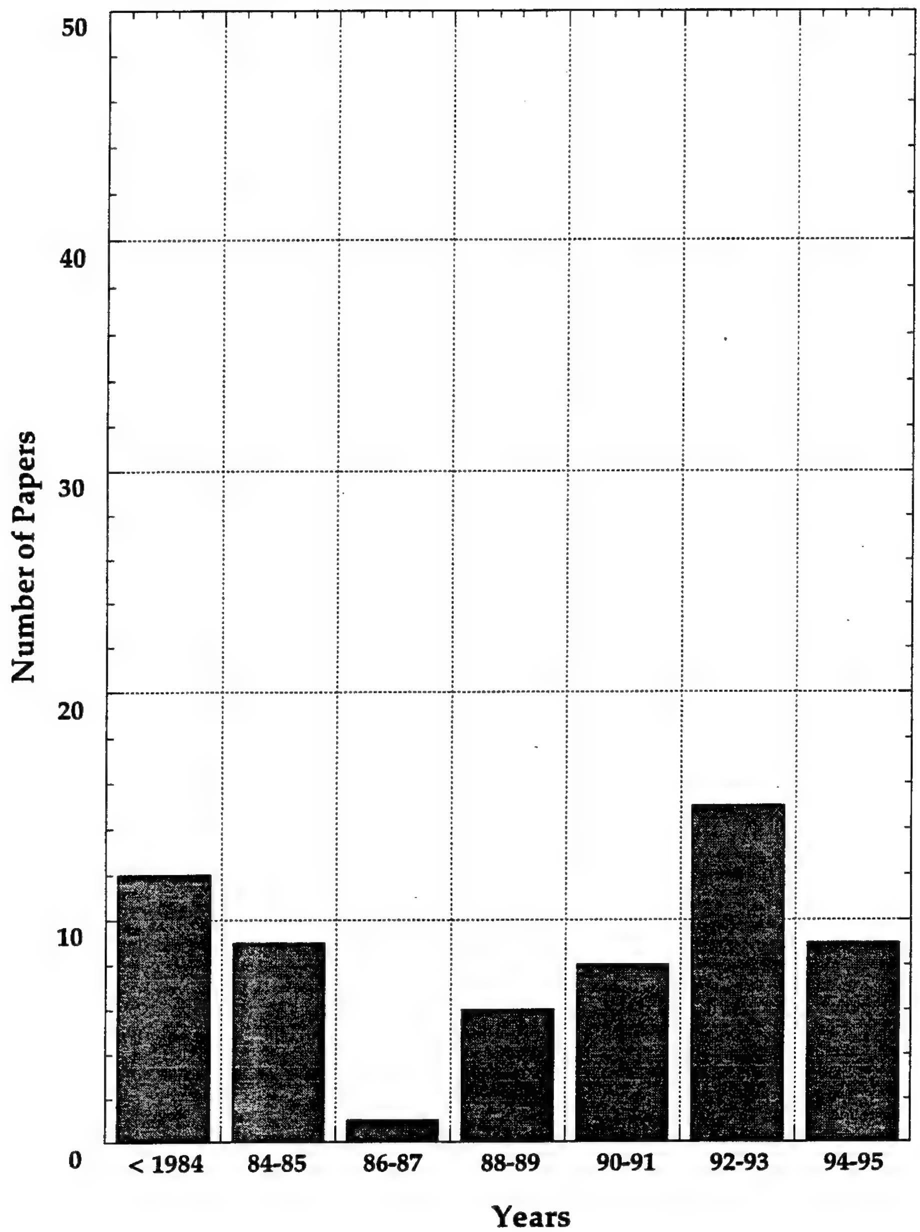


Figure 3-6. Number of papers over time for all devices in a neutron radiation environment.

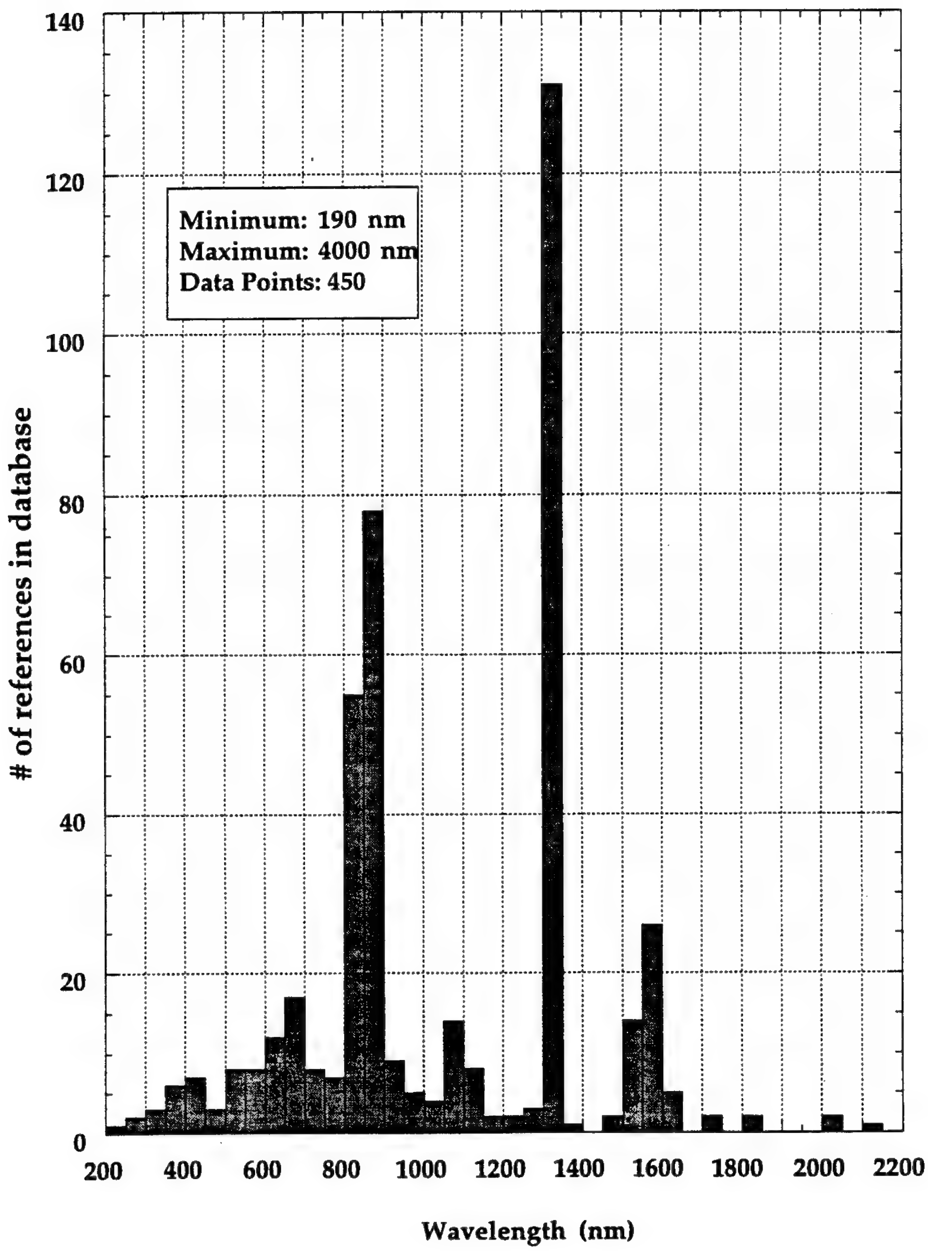


Figure 3-7. The wavelength of interest for all radiation tests.

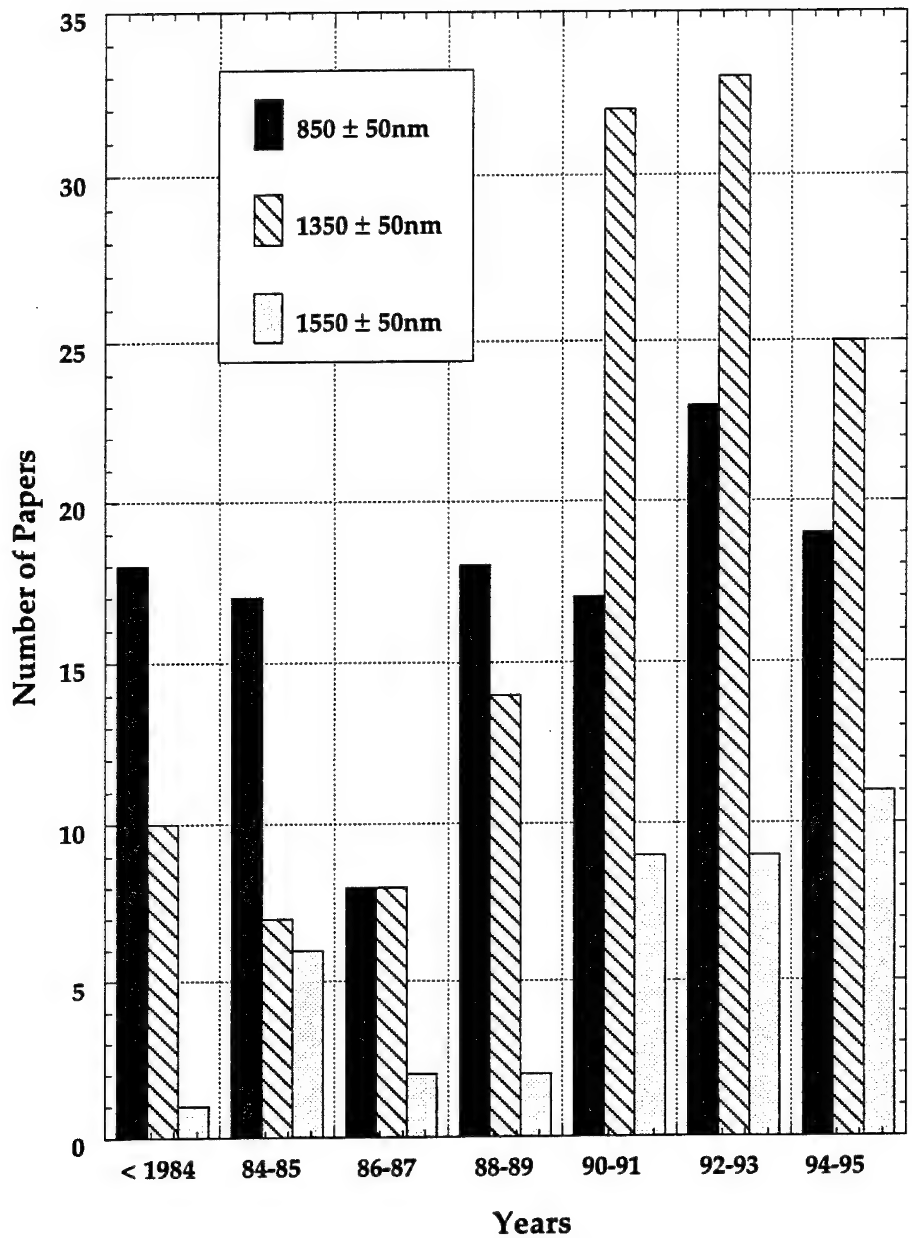


Figure 3-8. The wavelength of interest for all radiation tests over time.

## 3.2 DOCUMENTED RESEARCH STATUS ON SOURCES.

A light emitting diode (LED) is a very practical low cost source with a lower intensity and a spectral width about 10 times greater than the injection laser diode (LD). LEDs typically operate under a forward bias, where excess minority carriers are injected across the P-N junction and recombine with the majority carriers. The various mechanisms by which these injected minority carriers recombine determine the light output efficiency of the LED. Material impurities and growth induced lattice defects are two of the elements that reduce LED performance. The LED is less sensitive to power source fluctuations as well as temperature and humidity. These low cost LED devices also offer high reliability and reduced maintenance requirements.

In theory, the ionizing radiation effects on LEDs appear to be minimal. A research study by Barnes[22] in 1981 presented test results where high radiance, 820 nm emitting AlGaAs LEDs were unaffected by transient x-ray doses greater than $1x10^{12}$ rads/sec. Earlier measurements by Barnes[23] on a variety of LED devices demonstrated that after prompt x-ray pulses the only effect generated in these devices was photoluminescence. More recent studies[24-25] have shown that radiation induced displacement damage in the semiconductor lattice of LEDs is the most serious effect of a typical mixed radiation environment.

The key to understanding the detrimental effects of lattice damage on the performance of LEDs lies in an examination of the operating mechanisms of these devices. In an operating LED under forward bias, excess minority carriers are injected across the P-N junction where they recombine with majority carriers. The various mechanisms by which these injected minority carriers recombine determine the light output efficiency of the LED. If most of the carriers recombine radiatively to produce photons of energy roughly equal to the semiconductor energy band gap, then the device will be efficient. However, if the dominant recombination mechanism is non-radiative, then the light emission will be weak and the LED will be inefficient. A variety of centers can act as sites for non-radiative recombination events: unintentionally added impurities, dislocations, growth-induced lattice defects, and, most important for the present discussion, radiation-induced lattice defects.

Studies[26-27] in recent years agree with the earlier observations of the relative insensitivity of LEDs to both gamma irradiation and neutron irradiation, especially for high current density devices. Lischka[26], found little change in a variety of LEDs after exposure to Co-60 doses in excess of $10^{8}$ rads (Si) and $10^{13}$ neutrons/cm $^{2}$. These LEDs were high power, high speed devices with short minority carrier lifetimes that operate at high current densities. Thus, as pointed out above, one would expect them to be radiation hard. We emphasize again, that this is a fortuitous case where commercial development for higher speed has also resulted

in better radiation hardness. Sharma[28], also found that LED properties did not exhibit any change after exposures to $10^{6}$ rads (Si). In a study[29] of total dose and heavy ion SEU effects on spacecraft fiber optic MIL-STD-1773, the author showed that a fiber optic transmitter containing an AlGaAs LED was insensitive to radiation levels greater than 1 megarad.

The semiconductor LD emits a beam of light of high intensity with a narrow spectral width of approximately 20 angstroms. LDs also operate at high currents and have many electro-optical interface configurations. In agreement with earlier work on the effect of neutron irradiation on the near field pattern of operating laser diodes at nominal power levels, Carson and Chow[30] have shown that changes in the near field pattern occur only when the laser diode or laser diode array is operated at high power levels. After a large fluence irradiation of $1 \times 10^{15}$ n/cm$^{2}$, the threshold current has shifted markedly and much larger currents are required to reach an optical output power of approximately 1 W. These results suggest that neutron damage indirectly increases the susceptibility of the laser to facet damage.

The general issue of radiation hardness assurance for hybrids based on the more traditional Si very large scale integration (VLSI) technologies is currently undergoing much scrutiny and analysis. Thus, one can expect that similar issues for much newer technologies like photonics are only in their infancy, and that many interesting and challenging problems associated with radiation hardness assurance (RHA) of photonic/fiber optic-based hybrids will occur. Examples of such problems were demonstrated in recent work by Marshall[31] in which laser diode modules were subjected to proton and gamma irradiation. While there is an apparent decrease in laser efficiency with proton fluence, there is no change in the laser threshold current through the maximum proton fluence of $10^{13}$ p/cm$^{2}$. The authors point out that care must be taken in the interpretation of radiation results on hybrids that contain more than one type of device.

In analyzing the documentation for active sources it was noted that there was significant interest in survivable devices prior to 1984 and a resurgence in more recent years. Most of the testing prior to 1984 revolved around survivable components for military systems. More recent studies are focused on survivable spacecraft systems. Figure 3-9 provides a representation of the distribution of the collected documents for the past decade plus. These tests were performed in all radiation environments and include the specific components such as the laser or LED as well as the complete transmitter device with the laser or LED incorporated into the test package. Figure 3-10 has separated the environments as well as the operating wavelength at which the test was conducted. It can be noted that most of the total dose tests were performed at either 850 nm or 1300 nm with some interest at 1550 nm. In proton and prompt transient tests documents, research was undertaken primarily at 1300 nm with interest at 850 nm and at 1550 nm. Typically the 850 nm tests were performed earlier in the decade, while the 1550 nm tests were performed in recent years. Most of the neutron tests that were performed at 850 nm

were under the auspices of Sandia National Laboratory (SNL) and were performed in the late 70's and early 80's. The 1300 nm tests were primarily performed by NRL with a focus on survivable spacecraft systems. These research efforts were undertaken over the past 3 years.

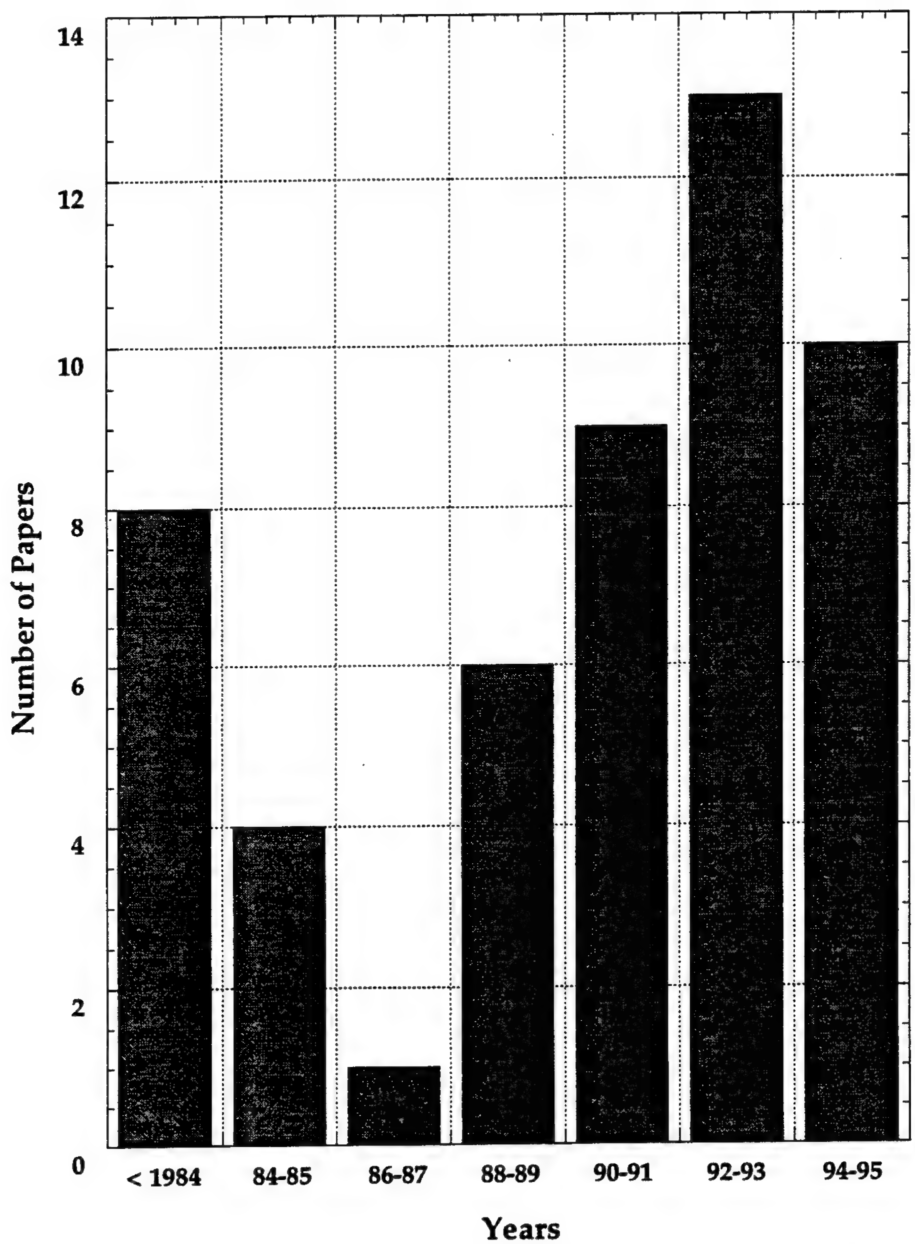


Figure 3-9. Number of papers over time for laser diodes and LEDS in all radiation environments.

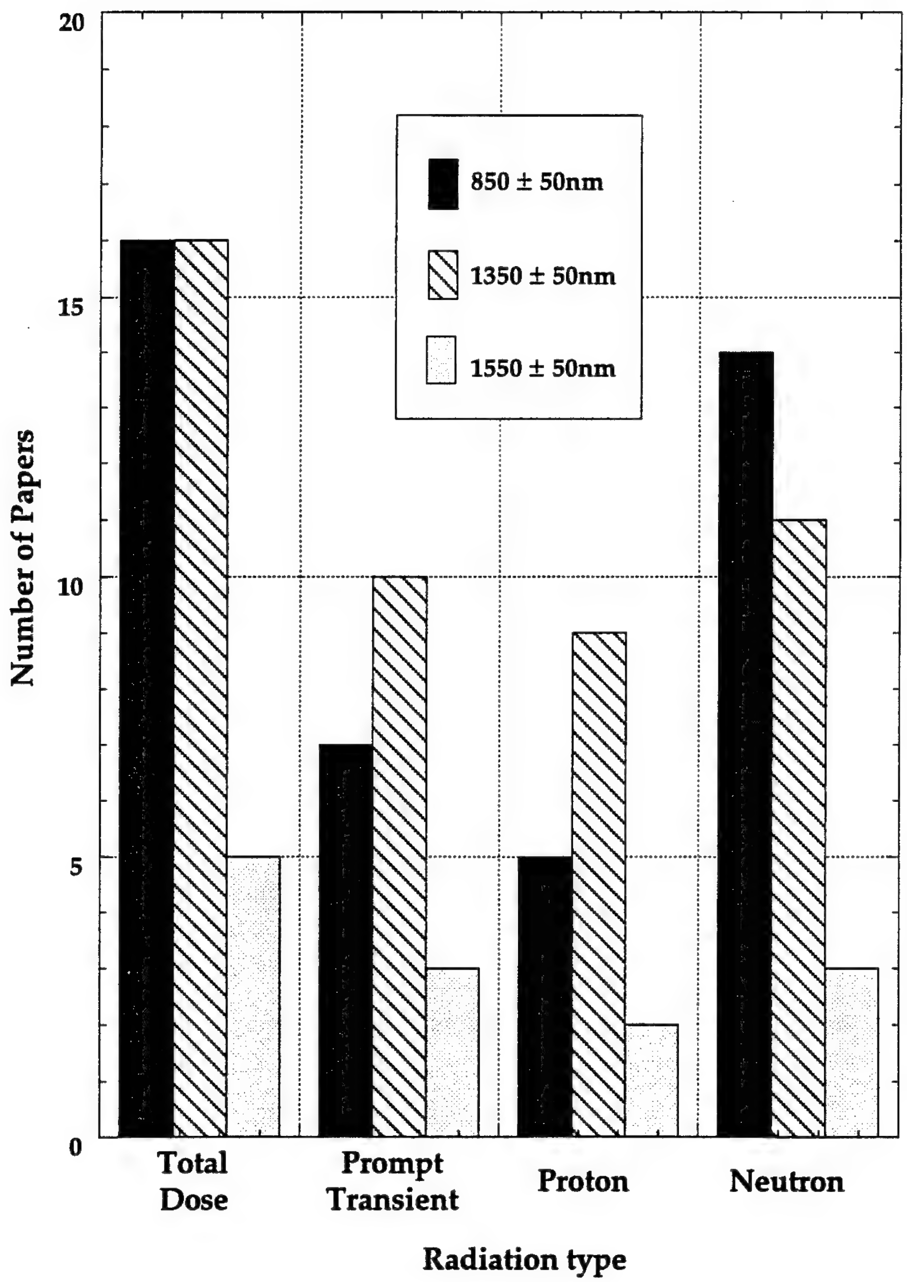


Figure 3-10. Wavelength distribution for LED and laser diode testing for each radiation environment.

## 3.3 DOCUMENTED RESEARCH STATUS ON COUPLERS AND CONNECTORS.

Radiation effects in optical components which provide the interconnection between active devices and connect fiber to fiber, device to fiber and fiber to device is not of principle concern. The extremely short path length in connectors and couplers (defined as passive branching devices) and the simple media provided by lenses, mirrors and filters imply that the transmitting material would have to be very sensitive to ionizing radiation to affect system performance. The greater issues associated with these components relate to mechanical degradation from long term radiation effects. Mechanical and optical breakdown from long term radiation exposures may directly affect system performance.

Connectors are basically designed and manufactured to minimize insertion loss as well as survive adverse mechanical performance requirements. Some connectors may rely strictly on the perfect alignment between fibers, while other designs integrate lenses or liquids into the connector to improve this alignment. Without any additional elements, the only element that may be effected by radiation is the small portion of the fiber in the connector ferrule. These types of butt-coupled connections will have induced losses similar to any fiber material, but will be insignificant in proportion to the length of fiber in a system. Epoxies that hold the fiber in place may be more prone to compositional breakdown from the radiation and cause greater design issues such as fiber positioning and optical alignments.

Passive branching devices or couplers can be classified into three basic types which include a transmissive type where the fibers are fused together, a reflective type where a quartz block is integrated into the coupler, and a ceramic coupler where the light is switched or transmitted through a ceramic chip. Biconically fused, tapered couplers are relatively small and are comprised solely of optical fibers. Fibers with different compositions may also be fused together to fabricate a wavelength division multiplexer (WDM) coupler. The induced absorption in these small devices is very low and insignificant when compared to long lengths of optical fibers. Fusion splices are considered permanent connections and undergo a similar process in fabrication as the fused tapered couplers. During any fusion process, considerable amounts of impurities are introduced into the fiber material. These impurities will increase the induced attenuation during radiation exposure. Fortunately, the region of impurity concentration is only a few millimeters and will have very little effect on system throughput.

A study[32] prepared by DNA during the late 1970's demonstrated that reflective star couplers which utilized a quartz rod or block showed no significant changes in transmissivity after different types of high radiation exposure. The amount of impurities in these bulk materials is minimized to maximize optical reflectivity and therefore minimize ionizing radiation effects in these devices. In recent studies[33-34] which investigated ionizing radiation effects in planar optical couplers, these results

also demonstrated that radiation damage is minimal in relation to overall system performance or sensitivity.

Several studies[35-37] have investigated ionizing radiation effects on lenses and filters. Results from an NRL study in the mid 80's indicated that Selfoc microlenses, when exposed to moderate levels of steady state irradiation, had induced losses as high as 1 dB at an operating wavelength of 850 nm. This study also reported that as the wavelength increased, a monatomic decrease in induced loss was observed. Lenses and filters are widely used in photonic systems to efficiently couple light from a source to the fiber or from one fiber to another. Since different materials and dopants are introduced into the lens to produce a gradient effect or change the focal length, it is important to choose the right lens that offer the optimum performance for the system while minimizing the induced losses from radiation. A typical borosilicate lens is usually loaded with impurities and subject to high induced losses. These impurities along with dopants contribute to the introduction of color centers during radiation exposure. These components can be fabricated to minimize any impurities and improved their radiation hardness. Typical pure quarts materials which are fabricated into microlenses have relatively few impurities and are resistant to ionizing radiation.

In analyzing the documentation that was collected for passive connectors and couplers to include lenses and filters, it is evident that there was no significant interest in survivable passive devices prior to 1984. In fact, very little testing was conducted on these devices until 1990. The greatest interest has begun in the past two years with a strong emphasis on WDM and fused tapered couplers. Some testing has been undertaken to evaluate the use of survivable connectors for nuclear power plant environments which combines high ionizing radiation fields with other adverse elements. Figure 3-11 provides a representation of the distribution of the collected documents for the past decade plus. These tests were performed in all radiation environments. Figure 3-12 has separated the environments as well as the operating wavelength at which a test was conducted. It can be noted that since most of the testing was performed in recent years that the most common operating wavelength is 1300 nm. The total dose tests were performed at all three wavelengths with most of the testing at 1300 nm with some interest at 850 nm and 1550 nm. In proton, neutron and prompt transient tests documents, research was undertaken primarily at 1300 nm with interest at 850 nm and at 1550 nm.

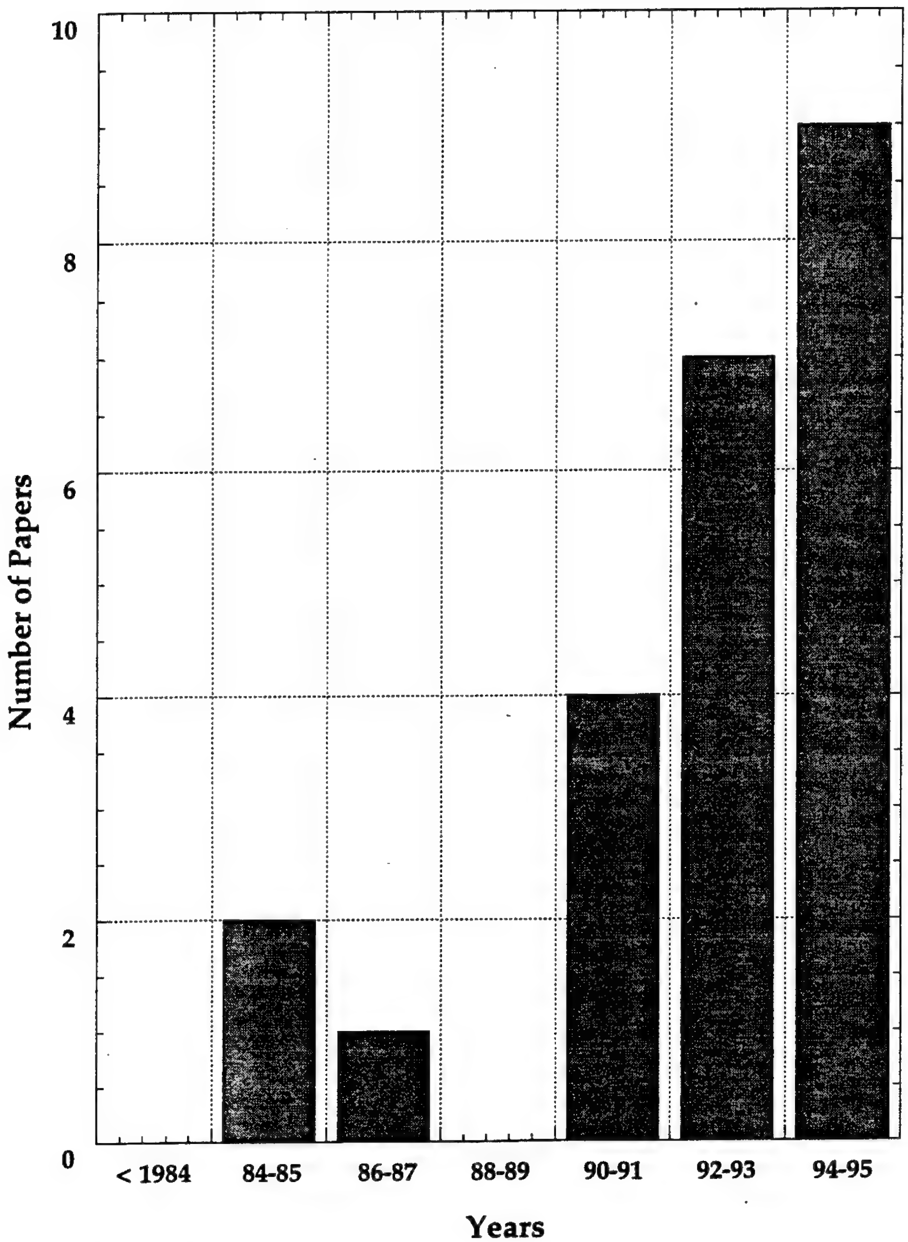


Figure 3-11. Number of papers over time for passive connectors/ couplers in all radiation environments.

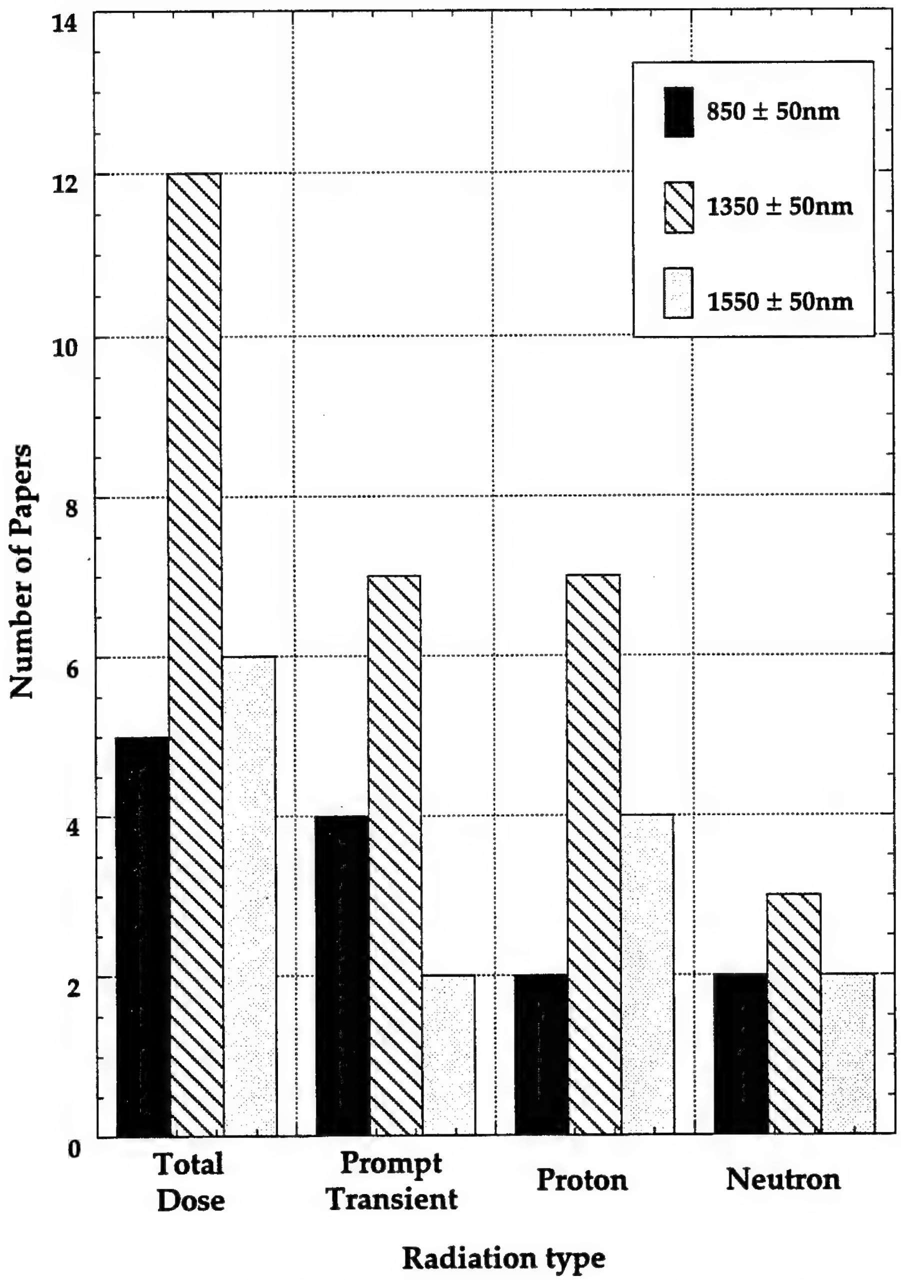


Figure 3-12. Wavelength distribution for passive device testing for each radiation environment.

## 3.4 DOCUMENTED RESEARCH STATUS ON INTEGRATED OPTIC (IO) DEVICES AND MODULATORS.

No radiation testing was performed on active IO/modulators prior to 1986. This is partly due to the fact that these are relatively new devices and only prototype models were fabricated before 1986. The past three years have shown a marked interest in radiation effects in these devices, with most of the work performed by the Phillips Laboratory (PL). Figure 3-13 shows the distribution of the collected documents over the past decade plus. Figure 3-14 provides a more detailed breakdown of the types of test results by radiation environment and by operating wavelength. Most of the tests were performed in a total dose environment at 1300 nm. Very little testing has been undertaken at 1550 nm as compared to reported testing at 1300 nm or in a neutron or proton irradiator. The next most common test was undertaken in a prompt transient irradiator and at 1300 nm. Since most of these devices are under development for advanced optical processing and computing systems, the 1550 nm and 1300 nm wavelengths predominate.

### 3.4.1 Documented Research Status on Polymer Waveguides.

3.4.1.1 <u>Polymer Waveguide Technology.</u> Polymers represent a particularly exciting material class for the manufacture of waveguides and electro-optic (EO) modulators. In addition to having attractive EO properties, polymers posses a demonstrated compatibility with many types of other material technologies, including III-V semiconductors. These attractive features, along with the general dramatic growth in work on optical systems and modulators, noted by Jabr[38], have led to a wide variety of demonstrations and research accomplishments in the use of polymers as waveguides and EO modulators.

A variety of polymers have been used to fabricate thin film waveguide and EO modulator materials and devices. In the case of waveguides where electro-optic modulation is not required, the fabrication consists of deposition, patterning and waveguide definition through implementation of appropriate refractive index variations. Depositions can be done in a variety of ways including dipping, roller coating, spraying or most frequently, spin coating onto a variety of substrates[39]. As noted above, patterning and area definition of waveguides is easily accomplished with standard photolithographic techniques.

Photoline gel polymer (PGP) waveguides have been developed with great success at the University of Texas[40,41]. This is not a synthetic polymer, but rather is a super polymer extracted from animal bones, and made up of thousands of 1 to 2 nm long amino acids. A solution is prepared of water and the PGP and spun onto a substrate. Various film thicknesses can be achieved by changing the PGP/water ratio or the spin speed of the coating process. Low loss waveguiding is achieved by a

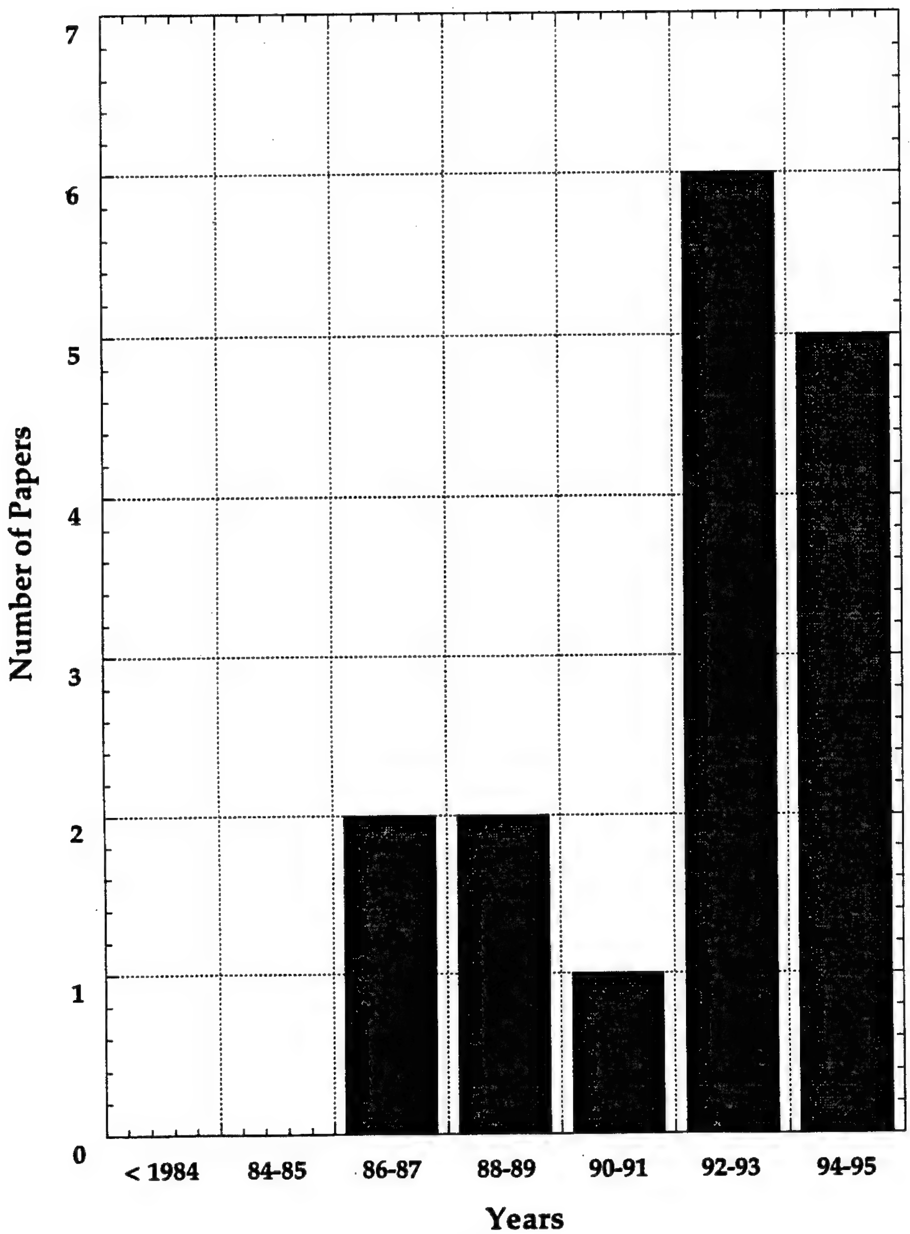

Figure 3-13. Number of papers over time for IO devices/ modulators in all radiation environments.

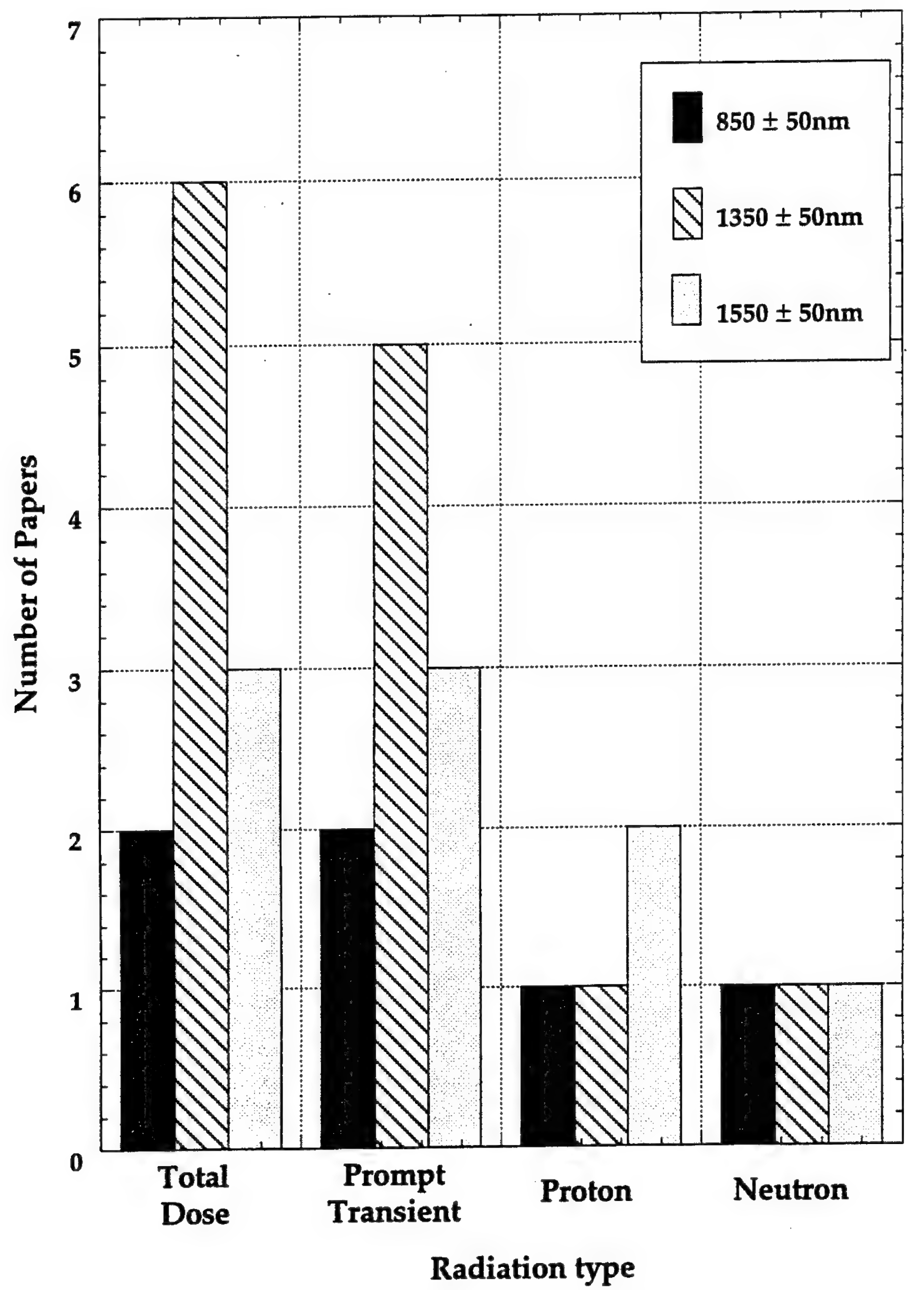


Figure 3-14. Wavelength distribution for active device testing for each radiation environment.

combination of wet and dry processing techniques that change the mass density, and hence the refractive index of the polymer through controlled absorption and dehydration processes. The resulting waveguides have a graded index profile and exhibit strong confinement with propagation losses as low as 0.1 dB/cm. Complex waveguide structures, such as channel waveguide arrays that allow wavelength division multiplexing (WDM) at 12 different wavelengths, have been constructed in this manner. Because of their high temperature stability and large usage base in the semiconductor industry, polyimides are an attractive class of polymers for waveguide applications. A variety of polyimides have been studied[42,43] for waveguide applications, and recent work[44] has shown that fluorinated polyimides are the most amenable for waveguide fabrication. Several methods have been used to define waveguiding regions in polyimide waveguides including electric field poling[45], also used for modulators[46], photobleaching, selective diffusion[47], reactive ion etching[48], direct laser writing[49] and negative imaging/wet chemical processing of photosensitive polyimides. Optical propagation losses as low as 0.5 dB/cm have been obtained in the photosensitive polyimides. Other materials that have been used to fabricate polymer waveguides include polyphenylene and photocrosslinking of liquid acrylate monomers to form solid polymer waveguides[50]. In the latter case, propagation losses as low as 0.01 dB/cm have been achieved in straight, multimode waveguides.

Similar materials have been used to construct polymer electro-optic devices with the additional requirement of inducing a large enough EO effect to allow the resulting structure to function as an electro-optic modulator. In addition, all-optical, as opposed to electro-optical, modulators have been fabricated from polymers. Prior to discussing these EO polymer materials, we briefly review some of the fundamental EO effects in optical materials.

Light Modulation for optical signal processing and other applications can be achieved with either the second order effect (Pockels effect) using applied electric fields, or the third order Kerr effect using high intensity light beams. In the first case, as we have noted above the applied electric field alters the refractive index which, in turn, causes a phase shift of the carrier light beam. For the Kerr effect, modulation is achieved by optical intensity-induced changes in the refractive index.

One of the more common types of modulators is the Mach-Zender interferometer in which an incoming light beam is split between two branches and then recombined at the output of the device. An electrode is placed over one branch so that an electric field can be applied to cause a phase shift of light beam in one of the branches. The phase shift in one beam then results in a modulation when the two beams are recombined due to the interference between the beams. Mach-Zender-like modulator structures have been fabricated with polymers by various vendors. An all-polyimide Mach-Zender modulator was constructed with an electrode length of 1.7 cm and operated at 200 MHz.

Paul, et al[51] used thermo-setting epoxies as a polymer host to fabricate phase modulators on Si substrates. Under the poling conditions used, the epoxy experienced additional curing resulting in a stable poled condition at room temperature. No change was observed in poled EO activity for more than a 1000 hours at 85°C. In a similar modulator development effort, Teng, et al[52] were able to demonstrate device operation at 40 GHz.

Other work[39] has also focused on the development of high bandwidth modulators using poled polymer structures. Bandwidths of 20 GHz were easily achieved. This research points out that although the voltage can be easily limited to less than 5 V for both polymer and $LiNb0_3$ modulators, polymer modulators are superior at the high bandwidths required for microwave modulation due to the fact that polymers have an optical refractive index equal to their microwave frequency refractive index. It follows that velocity (phase) matching in traveling wave microwave modulators can be nearly lossless in polymers, but $LiNbO_3$ microwave modulators are only of limited capability.

3.4.1.2 <u>Radiation Effects on Polymer Waveguides.</u> Much of the work[52-57] on radiation effects is concerned with the use of radiation as a tool to modify the properties of a particular polymer. For example, the UV-induced cross linking, following poling, helps to stabilize the EO properties of the poled polymer[55]. In addition, UV light has been used to attach the EO-active dopant to the polymer matrix, and to create refractive index patterns in polyimide films doped with UV-sensitive benzoin type photosensitizers. Other recently reported examples[56-57] of radiation-induced modification processes include: crosslinking of poly (tetrafluoroethylene) by x-rays and electrons, radiation-induced formation of diene, triene and tetraene from polyethylene in the presence of acetylene, electron irradiation-induced polymerization of fullerene films grown on GaAs, electron irradiation-induced gelation of blends of polystyrene - poly (vinyl methyl ether), and gamma ray irradiation and Xe and O ion implantation-induced grafting of styrene in poly (vinylidene fluoride) films. These few recent examples, together with a large body of work[53-55] in the earlier literature, clearly attest to the general sensitivity of polymers to various types of radiation. It is important to note, however, that in contrast with ionizing radiation effects in commercial Si MOS-based devices, relatively large radiation doses (i.e. several orders of magnitude) are required to cause significant effects in polymers.

Studies[58-61] have shown that radiation can also alter the electrical conductivity of the polymer. The electrical conductivity of polyaniline was shown to increase following gamma irradiation to 30-40 megarads. Electron spin resonance (ESR) results indicated that electrically active sites increased at the same rate as the electrical conductivity suggesting that charged sites facilitate a hopping conductivity. A study[58] of the effect of gamma irradiation and electric field on the AC conductivity of polyvinylidne fluoride revealed that irradiation decreased the conductivity while

the application of large electric fields increased the conductivity. In another study[59], it was found that gamma irradiation to 10 megarads altered the conductivity of polyacrylamide treated with metal-chloride compounds, but not that of untreated polyacrylamide. Whether gamma irradiation caused an increase or decrease in conductivity in the treated material depended on a variety of factors associated with the treatment. In yet another study[61] have also shown that gamma irradiation affects the resistance of polymer-based resistors over a fairly wide range of dose, even down to kilorads, depending on nature of the resistors.

In the only study[62] specifically intended to determine the effects of radiation on electro-optic (EO) polymers, Kanofsky and Herman examined two types of EO polymers before and after 3 MeV electron irradiation to a maximum dose of 44 megarads. The first type of polymer studies was a poly(methyl methacrylate) (PMMA) host doped with a guest chromophore, Disperse Red 1 (DR1) dye, while the second was a syndioregic cinnamamide main chain polymer in which the EO active material is incorporated in the polymer main chain. Both polymers were poled near the glass transition temperature, which was 95°C for the PMMA and 208°C for the main chain material. The extent of second order EO activity remaining in the polymers at any given time, and also following irradiation, was measured by detecting the intensity of second harmonic generation (SHG) at 532 nm using a double Nd: YAG laser (1064 nm).

Detection of the effects of electron irradiation were complicated by the fact that the temperature at which the samples were held (this temperature is not given, but is probably room temperature) was high enough to cause significant decay of the EO activity over a period of days, especially for the PMMA samples. Thus, the poled state of the samples was not very stable. Following irradiation of the PMMA, additional decreases in the EO activity were observed. In the case of the main chain polymer, no effects of irradiation were seen at the maximum dose of 44 megarads. The authors also measured the birefringence of the samples and observed a radiation induced decrease in birefringence in the PMMA samples, another indication of a reduction of the fraction of dopants in the poled state.

Several questions remain concerning the observations reported in this work. With regard to the experimental procedures, pertinent information that is not provided includes: the temperature at which the samples were held during measurement and irradiation, the energy density of the Q-switched laser beam and the dose rate for flux of the electron beam. The intensities of both the laser and electron beam could affect the results by temporarily raising the temperature of the sample if the energy densities were high enough. In addition, a relatively strong Q-switched laser could cause the same effects as the electron irradiation. We have already noted several studies where UV and laser light cause similar effects. Although the 1064 nm light is not highly absorbed, the 532 nm light is strongly absorbed. The authors do not say whether or not they made a sequence of repeated measurements within a

short time to detect whether or not the laser beam was having any permanent effect on the samples.

The electron-irradiation results in the PMMA did not reveal a clear trend in the reduction of the magnitude of the EO activity with dose. For example, two samples irradiated to only 3.7 megarads showed greater change than all the samples irradiated to higher doses. For another set of two samples the change observed at 22 megarads was greater than the change seen at 44 megarads.

In attempting to explain the radiation-induced reduction of EO activity in the PMMA, the authors state that bond breakage may be playing a role since "chain scission in PMMA under irradiation, with no evidence of crosslinking, has been known for some time." The references the authors referred to for this statement are dated 1953 and 1960. However, our review of recent work[55-57] has clearly shown that radiation-induced crosslinking is widely observed and in fact has been used to further stabilize the poled state rather than making it less stable.

3.4.2 Documented Research Status on Insulator Based Modulators.

Clearly, the development of optical modulators has been dominated until recently by $LiNbO_3$ in terms of both the longevity of research and development, and the variety of commercially available devices. However, there are still problems with this technology, and challenges to be met by continuing research. As recently as 1993, with regard to $LiNbO_3$, it was stated that "predictable and reproducible performance has been difficult to achieve and maintain, in spite of the fact that $LiNbO_3$ research goes back nearly 20 years"[63]. It is not a highly controversial statement to say that $LiNbO_3$ process technology will probably never reach the level of precision and control that has been achieved already by semiconductor process technologies. This, of course, is one reason why we suspect that ultimately the high level of recent research activity on semiconductor modulator structures will lead to a dominance over $LiNbO_3$ by these materials, especially in integrated devices where electronic digital functions are placed on the same chip as photonic functions.

By far the greatest number of radiation effects studies[64-73] have been performed on photonic devices fabricated from the insulator materials, $LiNbO_3$ and $LiTaO_3$. We emphasize that this statement is only true if one does not include the large amount of radiation effects work that has been done on related III-V semiconductor structures like LEDs, lasers, detectors and digital devices. As we will see, however, most of the work on radiation effects in $LiNbO_3$ has been on relatively simple structures, basic materials and couplers without electrodes. Thus, much remains to be done in order to build on the present body of work.

Our review of materials and basic device operating characteristics suggests that one should expect that radiation would affect the operating characteristics of $LiNbO_3$ and $LiTaO_3$ devices. The waveguides in these materials are formed, whether by metallic

indiffusion or proton exchange, by alteration of the impurity and defect distributions within the guiding region. These distributions should also be susceptible to alteration by the radiation-induced introduction of defects and by the trapping of radiation-generated electrons and holes at color centers in the guiding region. We have already noted that optical radiation can cause changes in waveguide characteristics through the photorefractive effect[71]. Thus, one would expect similar effects for gamma rays, x-rays, electrons and protons.

It is also apparent that the properties of $LiNbO_3$ are sensitive to external effects through the coupling of the optical properties to other parameters such as temperature (pyroelectric effect) and stress (piezoelectric effect). This general sensitivity of the optical properties of $LiNbO_3$ and $LiTaO_3$ to external parameters suggests that these same optical properties may be susceptible to the effects of radiation.

It is interesting to contrast the potential for radiation effects in $LiNbO_3$ devices with the well-known effects of radiation on Si semiconductor devices, such as CMOS VLSI circuits and Si solar cells. Si devices, in their unhardened commercial form, are quite sensitive to ionizing radiation, exhibiting degradation at only a few kilorads. However, Si devices are very pure and highly controlled during the fabrication process. Thus, one expects that a few defects or trapped electrons/holes may be significant relative to the few defects already present. In contrast, both $LiNbO_3$ and $LiTaO_3$ are quite impure materials compared with state-of-the-art Si. Impurity levels in $LiNbO_3$ and $LiTaO_3$ , whether added intentionally as in Ti indiffusion, added inadvertently during growth and fabrication or merely present in raw material, are much higher, so that radiation-induced defects and trapped charged carriers would not affect $LiNbO_3$ properties until they reach levels comparable with the impurity and defect concentrations present prior to irradiation. As we will note, this is borne out of the total ionizing dose studies of these materials. Thus, while we should not be surprised to see radiation effects in $LiNbO_3$ and $LiTaO_3$, these effects will be observed at radiation levels much higher than is typical for Si-based devices.

As is typical of an emerging technology, most of the radiation studies[68-71] of $LiNbO_3$ and $LiTaO_3$ have been concerned with radiation-induced changes in materials properties rather than device effects. It will become evident in our review that bulk materials and relatively simple waveguide structures with no electrodes have been essentially the only types of $LiNbO_3$ and $LiTaO_3$ structures that have been examined following radiation exposure. In fact, one of our principal recommendations is that radiation effects studies of more complex structures be initiated in parallel with a continuation of the examination of basic radiation effects in these materials.

Many early radiation effects studies[70-71], and also a few recent ones, focused attention on the effects of radiation on the absorption spectrum of $LiNbO_3$. Two absorption bands at approximately 387 nm and 480 nm appear to be influenced by ionizing

radiation. The band at 480 nm is associated with the presence of Fe and is therefore related to photorefractive effects in $LiNbO_3$. Ionizing radiation causes this band to grow when the doses are above $10^5$ rads. The growth is more prominent in Fe-containing crystals, and is absent from crystals doped with Mg, even if the Fe concentration is significant. The 480 nm band is susceptible to both photobleaching and thermal annealing at about 200°C. Recall that we have noted that doping with Mg reduces the photorefractive effect in $LiNbO_3$, suggesting a relationship between the 480 nm band and photorefractive effects.

More recently, radiation-induced absorption at 1061 nm in z-cut $LiNbO_3$ and $LiTaO_3$:MgO following a burst of radiation from a pulsed nuclear reactor has been studied[74]. It was shown that the effect of neutrons from the radiation pulse, limited to fluence levels less than $1x10^{13}$ n/cm$^2$, was negligible. This is not surprising since it has been shown that fluences of the order of $10^{16}$ n/cm$^2$ were required to affect the absorption spectrum. All of the effects observed in this study were attributed to the prompt gamma dose that was less than 7.5 kilorads per pulse. As for the 480 nm band, the radiation-induced absorption at 1061 nm was much less in MgO doped $LiNbO_3$. The decay of the radiation-induced absorption was non-exponential and occurred over a broad range in time and appeared to be composed of the decay of a variety of color centers with differing decay constants. This extended decay of radiation-induced absorption was similar to that reported earlier for pulsed electron bombardment of pure $LiNbO_3$, and by Roeske, et al[75] more recently for pulsed electron irradiated Ti:$LiNbO_3$. Thus we see that prolonged decay of radiation-induced absorption is generally characteristic of $LiNbO_3$. It is also important to note that while very large doses of steady state ionizing radiation are necessary to produce significant changes in absorption, pulsed irradiation at levels of a few kilorads can produce significant transient absorption. Thus $LiNbO_3$ behaves similarly to optical fibers in the sense that fiber also exhibit strong transient radiation-induced attenuation.

As Part of the extensive work done on radiation effects in $LiNbO_3$ at the Air Force Phillips Laboratory, Taylor, et al[64-69] have examined the decay of radiation-induced attenuation (absorption) in $LiNbO_3$ . These measurements, and others we will review, were performed on $LiNbO_3$ waveguides rather than bulk materials as in the studies noted above. Thus, an important difference is that the material is non-uniformly doped either with Ti or by the proton exchange process, and the attenuation observed in a beam exiting a waveguide is influenced not only by color center absorption, but also by evanescent leakage into the substrate, possibly the result of radiation-induced changes in the refractive index. However, the results in waveguides and bulk materials are similar in the broad sense that attenuation was observed to exhibit a slow recovery extending well beyond the duration of the radiation pulse. Taylor used a geminate recombination model to fit attenuation recovery data, which result in a $t^{-1/2}$ dependence in contrast with Brannon's[74] observations of a $t^{-1/4}$ dependence.

More recent studies by Taylor[76-77] and others[78-81] used structures with more than one waveguide, however, they only measured the output from one of the guides following irradiation. Because of the relative insensitivity of $LiNbO_3$ and $LiTaO_3$ to permanent damage, most of these studies have focused on transient radiation effects. Broadly speaking, the common result observed in all these studies for both $LiNbO_3$ and $LiTaO_3$ was that the waveguide attenuation increased during and immediately following the ionizing radiation pulse, and then recovered relatively slowly, with the induced attenuation lasting milliseconds or longer. Since materials studies, noted above, have shown the same basic result due to color center introduction, it is logical to conclude, as Taylor has done, that at least some portion of the induced waveguide attenuation is due to radiation-induced color center formation and subsequent anneal. In addition to waveguides formed by Ti diffusion into $LiNbO_3$ long lived, radiation-induced attenuation has been observed in proton exchanged $LiTaO_3$[82-83] and proton exchanged $LiNbO_3$[84-85]

As yet, it is difficult to draw any conclusions about the relative radiation hardness of $LiNbO_3$ and $LiTaO_3$ because the differences in radiation response of the two materials have not been consistently large and in the same direction. In addition, in two of the studies where both materials were examined the wavelengths at which the two materials were examined were different; 850 nm for $LiNbO_3$ and 1300 nm for $LiTaO_3$. Under these conditions, it is not surprising that the $LiNbO_3$ attenuation was greater than that of $LiTaO_3$ waveguides. However, in a recent study Padden[67], et al concluded that under the conditions of their testing, $LiTaO_3$ was significantly more radiation resistant than $LiNbO_3$.

Recent work[86-87] by the Phillips Laboratory (PL) Group has focused on the effects of pulsed irradiation on the energy transfer between waveguides (crosstalk) in $LiNbO_3$ and $LiTaO_3$ directional couplers. In the initial phase of this work, results were reported out to a few μsec for light intensities exiting from both output waveguides (1300 nm laser light input only to a single waveguide) during and after bombardment by ionizing radiation pulses that delivered 15 kilorads/pulse to the sample. For the z-cut, y-propagating $LiNbO_3$ devices, the input beam was primarily TE polarized so that for the active length of the coupler used in these experiments, 22 mm, there was significant transfer of energy from the input throughput waveguide to the second crossover guide. Following 15 ns wide pulse of 16 MeV electrons to 15 kilorads, there is large drop in the light intensity exiting from both the throughput and crossover waveguides. The relative magnitude of the decrease depends on the launch conditions and the polarization of the input beam.

It is important to emphasize that these high dose, pulse radiation experiments are exceedingly complex and difficult to interpret because of the many interrelated parameters that can change during and following the pulse. The PL Group has attributed the observed effects to a combination of factors including color center introduction, refractive index changes and photorefractive effects, all of which are interrelated. In addition, as we have noted earlier, the pyroelectric effect in z-cut

$LiNbO_3$ is strong, and one expects that the deposition of a large amount of energy in a short time into these $LiNbO_3$ couplers will cause temperature increases and temperature gradients to be present in the sample. The samples are usually not uniformly exposed to the pulsed electron beam so that stress and temperature gradients can be expected across the boundary of the electron beam impact area. Even if the active coupling region is uniformly irradiated the gradients introduced can affect the time history of the waveguide behavior and that portion of the exiting light beam that is detected. For example, suppose that the refractive index of the guides inside the irradiated area changes significantly as the PL Group correctly suggests. However, the remaining portions of the guides outside the irradiated area, but inside the coupler, will have a different refractive index. Thus, one is faced with the additional complexity of having lengthwise sudden variation in the refractive index along the guides. This is roughly equivalent to having two different waveguides butted end to end, as at the coupler-fiber connection, during and immediately after the pulse.

In light of these complexities, it is interesting to further consider the implications of the results observed by the PL Group, especially with regard to radiation-induced photorefractive effects. During and immediately after the radiation pulse, the irradiated region of the coupler is flooded with electron-hole pairs. The holes are essentially immobile because of their low mobility in $LiNbO^3$, but the electrons can move through the crystal at room temperature (it has been argued that electron mobility is even higher in the waveguides because of the presence of Ti). Most of the electrons will recombine with holes in a short time, but a significant number will migrate through the crystal creating a temporary redistribution in space charge, and also becoming trapped at color centers. It is reasonable to assume that during and immediately after the radiation pulse, the extremely high density of electrons and holes present will tend to make the crystal uniform and minimize the effect of the Ti dopant used to create the waveguides. thus, it is also reasonable to expect that there will be strong leakage out of the waveguides because their ability to confine the light waves will be reduced by the overwhelming effect of the high density of electrons present. While this will lead to dissipation of some of the light into the substrate, it will also result in stronger coupler of the light into the crossover waveguide as observed by the PL Group.

The fact that there is separation of the electron-hole pairs due to drift of the electrons in internal electric fields or due to diffusion because of strong diffusion gradients present, and that there is undoubtedly trapping of electrons at $Fe^{+3}$, acceptor centers strongly suggests that there will be a radiation-induced photorefractive effect, an explanation that Taylor has advanced in several of the PL Group papers. The occurrence of photorefractive effect depends on the ratio of $Fe^{+2}$ to $Fe^{+3}$ which will surely change during and immediately after exposure to an intense pulse of ionizing radiation. The iron acceptor, $Fe^{+3}$, has a large electron capture cross section so that one expects the density of $Fe^{+2}$ to increase following radiation exposure. We have already noted that there is a radiation-induced permanent attenuation in the absorption bands associated with the presence of iron.

In addition, decay of photorefractive effects are long term, and laser-induced photorefractive effects typically last long after the laser beam is turned off. Thus, the long term residual effects observed after pulsed electron irradiation have a time scale similar to that of photorefractive effects.

Unfortunately, although there are reasons to expect a pulsed irradiation-induced photorefractive effect, there are also reasons why it may not occur, at least in the traditional sense. Although it is reasonable to expect a radiation-induced alternation in the $Fe^{+2}/Fe^{+3}$ ratio, it is not clear how the second necessary step, space charge separation, will occur within the bombarded coupling region of the device. In the early development of the physical model for the photorefractive effect, similar difficulties were encountered in explaining the effect. The early model advanced for the photorefractive effect by Chen[41], which is still essentially correct, proposed a two step process in which electrons are photoexcited by a light beam from $Fe^{+2}$ donors to the conduction band of $LiNbO_2$. In the second step, the electrons move to other locations in the crystal where they are trapped primarily at $Fe^{+3}$ center producing a space charge separation that results in an electric field that modifies the index of refraction through the electro-optic coefficients. Later authors went to some lengths to explain the existence of a sufficient driving force to preferentially move the electrons away from the Fe atoms when there were no obvious applied or built in electric fields to cause drift of electrons. Another puzzling result that required a similar explanation was that with strong light beams, photorefractive effects are also seen in pure $LiNbO_3$ that contains very little iron. One explanation that applies to holographic grating formation with two interactive laser beams is that since there are light and dark regions in the crystal due to periodic interference between the beams, the electrons released in the light regions will respond to the diffusion gradient and migrate to the dark regions. Thus, one requires either some driving force (an internal or applied electric field), or non-uniform illumination to provide a diffusion gradient.

In spite of these various mechanisms for the separation of charge, it is not obvious how the space charge build up will occur during and immediately after intense pulses of electron irradiation that flood the bombarded region with electron-hole pairs. One would expect that all the acceptor impurities such as $Fe^{+3}$, in the bombarded region would be filled with electrons so the there would be a uniform distribution of primarily $Fe^{+2}$ in the bombarded region. It is important to note that unlike laser-induced photorefractive effects, in which photoexcitation of electrons to the conduction band is from the impurities like iron (the Chen model), in the case of high energy electrons, direct band gap excitation and creation of electron/hole pairs takes place. In addition to filling trapping centers, during the 6.6 sec of repetitive radiation pulses, electrons will drift due to internal electric fields and by diffusion out of the bombardment region into adjacent areas of the crystal. As in the non-uniform illumination case mentioned above, the non-uniform bombardment provides an diffusion gradient. This diffusion process could result in electrons diffusing not only laterally outside the waveguides but also length wise down the guides in both directions away from the bombarded active coupling region of the

device. Thus, the end result may be photorefractive effect established between the bombardment region, which contains primarily $Fe^{+2}$, and the remainder of the crystal (including the non-coupling portions of the waveguides), that contains some concentration of $Fe^{+3}$. The movement of the electrons out of the bombardment region will induce a gradual change in the ratio of $Fe^{+2}$ to $Fe^{+3}$ across this boundary. If this scenario were valid, the electric field created by the photorefractive effect would be located primarily across the boundary of the irradiated region, and would be in the opposite direction of the traditional photorefractive effect. The resulting changes in refractive index due to the electro-optic effect would not affect the coupling region, but may lead to increase light leakage out of the guides away from the active region of the device. This alternative scenario for the photorefractive effect in these irradiated devices suggests that it is not clear exactly how they will be affected by any radiation-induced photorefractive effect. The important factor to emphasize is that intense, pulsed irradiation with high energy electrons does not correspond to the conditions for establishing the traditional photorefractive effect, and so this explanation must be used with caution.

Finally, we should note that there is precedent for attributing increases in crosstalk to photorefractive effects. Schmidt[89], et al studied optically-induced crosstalk at 633 nm and 1060 nm in reverse-$\Delta\beta$ z-cut, Ti diffused $LiNbO_3$ couplers. Significant increases in crosstalk were observed under a bias of 25 V and 633 nm optical power of 20 nW (0.2 W/cm$^2$) over a period of 60 min. The crosstalk increased rapidly during the first 5 min and then saturated at a level of about -13 dB. Space charge build up between the illuminated guide and the second guide was attributed to photoconductive motion of carriers under the influence of the applied field. Later work[90] on optically-induced photorefractive effects in a Mach-Zender interferometer attributed these effects to photovoltaic (no applied field) effects rather than a photoconductive mechanism. We emphasize again, however, that the steady build up of photorefractive effects due to laser photoionization of Fe centers may be quite different from intense, high energy electron bombardment.

3.4.3 Documented Research Status on Spatial Light Modulators (SLM).

3.4.3.1 <u>SLM Technology.</u> Spatial light modulators (SLMs) are diverse and complex class of devices that have in common the property that they provide a controlled and high speed method of changing the direction of a light beam, and also a method of spatially storing information. Acousto-optic (AO) devices, including AO Bragg gratings, are an important class of SLM devices that are fabricated in a variety of materials. The AO effect occurs in photoelastic materials like $LiNbO_3$ and $TeO_2$, and is one form of stress-induced birefringence that is exhibited by these materials. When an acoustic wave, which can be either a longitudinal or transverse traveling wave, passes through a photoelastic material it causes a traveling wave of refractive index variations whose maxima and minima correspond with the peaks and troughs in the acoustic wave. These variations can be used to diffract an optical beam, the basis of operation for Bragg cells. An acoustic wave can also propagate as a

surface acoustic wave (SAW) confined two a near-surface region like an optical waveguide. These longitudinal and transverse SAW modes are an important class of acoustic waves because they can interact efficiently with waveguided optical beams.

SLMs are a key component in many types of optical systems. In particular, they are critical for parallel optical and neural computing architectures. Very broadly, they consist of components that allow one to spatially modulate optical fields, usually in the form of a matrix or grid of parallel optical signals. SLMs consist of an addressing material and a material whose optical properties can be modulated so that the read beam can be altered by the properties of this material. Important properties of an SLM are high spatial resolution (greater than 100 line pairs/mm), large size (1000x1000 pixels or more), high speed (MHz frame rates), high extinction ratios (greater than 1000:1), gray level capability, low power and low cost. As in any complex electronic device, it is difficult to achieve all of these desirable properties in one device, and compromises are necessary depending the specific application.

One way of categorizing SLMs is according to whether they contain a solid EO material or a liquid crystal for light modulation. Liquid crystal-based SLMs require only low voltages relative to the requirements for solid crystals like $LiNbO_3$ , but have relatively low resolution and low frame rates. However, these characteristics are rapidly improving as extensive research continues to take place. For example, Nippon Telephone and Telegraph (NTT) has recently reported an optically addressed ferroelectric liquid crystal light valve (LCLV) with frame speed of 2000 frames/sec. Some of the important types of SLMs are discussed below.

The LCLV[91] is an optically addressable device which typically consists of a complex sandwich of thin film layers made up of glass or fiber optic face plates, transparent conductors, a photoconductor to allow optical addressing (writing) (CdS or amorphous Si, for example), a light blocking layer so that the writing light is blocked from the read side, a dielectric mirror to reflect the read beam back out, and the twisted nematic liquid crystal (LC) through which the read light passes on its way to and from the mirror. With no write beam-induced voltage from the photoconducting material (off state), the LC molecules, which are rod-like and have a birefringence related to the molecular orientation, are all oriented parallel to the surface of the conductor plates, and the read beam does not experience any polarization change passing through the LC. The write beam reduces the resistivity of the CdS photoconductor so that a voltage appears across the LC resulting in a twisting of the molecules toward the direction perpendicular to the plate surface. The molecular birefringence then causes a change in polarization of the read beam as it passes through the LC into and out of the structure. Polarizers and analyzers can be used to provide intensity or phase modulation of the altered read beam. A typical LCLV has a resolution of 40 to 60 line pairs/mm, a contrast ratio greater than 100:1, and a response time of 15 to 50 ms, limited by the time response of the nematic LC.

The liquid crystal television (LCTV) is a 90° twisted nematic liquid crystal sandwiched between two parallel polarizers. When no electric field is applied, the plan of polarization for linearly polarized light is rotated through 90° by the twisted LC molecules, and no light is transmitted through the second polarizer. Under an applied electric field, the twist of the liquid crystal molecules is altered, resulting in a greater fraction of the light maintaining the initial polarization direction and thus passing through the second polarizer. The primary advantage of typical commercial LCTVs is their low cost. However, the light transmission efficiency is only about 4% and the maximum contrast is about 10, precluding their use in certain photonic applications.

Future high speed, parallel architecture computing systems will take advantage of the attributes of both optical signal processing and Si-based digital signal processing. Toward that end, work has been going on to integrate SLMs[92] with Si CMOS technology. The principal challenge is mating the various technologies on a single substrate so that one obtains a high performance SLM integrated with digital processing elements. Various schemes have been proposed and attempted using both hybrid and monolithic concepts to integrate light modulators with light detection and logic processing circuits. For those devices that propose using an EO modulator with standard photonic devices, such as laser diodes and detectors, our discussion of radiation effects in modulators and other photonic devices can be referred to for relevant information. Other schemes involve more esoteric techniques using ferroelectric liquid crystals imbedded in a Si substrate, and these applications must be considered in this section.

Commercially available magneto-optic SLMs (MO SLM)[93] consist of a 2-dimensional array of MO shutter elements made up of epitaxial layers of magnetic garnet on a nonmagnetic substrate. In the presence of a strong magnetic field the shutter magnetic domains orient themselves along field. When a linearly polarized light beam traverses the magnetic lines of a magneto-optic element, its polarization direction changes due to the Faraday effect. The polarization modulation of the light beam is transformed to a light intensity modulation or to a phase modulation by a polarizer/analyzer combination placed on the two sides of the SLM. These devices do not transmit a large fraction of the light beam even in the on-state. However, they are relatively fast, and 128x128 commercial MO SLMs have been run at 350 frames/second.

The microchannel SLM (MSLM)[94] is an optically addressed SLM consisting of a photocathode as an address material and an EO crystal such as $LiNbO_3$ as a modulating device all in a vacuum sealed tube. The photocathode is used as a 2 dimensional photoelectric converter and a microchannel plate is used to multiply the 2 dimensional photoelectric signal that impinges on the $LiNbO_3$ for EO modulation. The MSLM can operate at very low writing light level, but with a high readout light intensity at the same wavelength. The MSLM can perform image addition, subtraction, and memory retention.

3.4.3.2 Radiation Effects on SLMs. It is not surprising that very little work has been done on radiation effects on SLMs. These devices represent a new field of research and device development, and most SLMs are quite complex devices. Their complexity and variety make it difficult to perform definitive radiation effects studies, and to interpret the results of such studies in a manner that can be generalized and applied to a variety of SLMs. The following discussion reviews the work in the literature on radiation effects on SLMs, and discusses the radiation effects implications of the operating characteristics and structure of SLMs.

Early studies[95-97] of radiation effects on quartz and $LiNbO_3$ surface acoustic wave (SAW) delay lines investigated displacement damage from neutrons, Co-60 gamma ray effects and transient ionizing radiation effects. The results of these studies indicated that the delay lines were essentially immune to permanent radiation effects, but that some devices exhibited a response to high dose rate transient radiation bombardment. While the immunity of these devices to irradiation is encouraging, one cannot conclude that state-of-the-art SAW devices would behave similarly because of the improved quality of more recent devices, and because these were relatively simple delay lines rather than narrow band devices such as resonators or filters.

More recently, Hines[98], et al examined various types of quartz SAW resonators for total dose effects using a variety of radiation sources. Several device characteristics were measured as a function of dose and no parameter showed any change below 100 kilorads. Swept quartz substrate devices showed a negative shift in frequency at which a certain insertion loss is measured relative to a control device. However, these changes were small, even at 10 megarads. The non-swept quartz devices showed much stronger positive frequency shifts to as much as 120 ppm at 10 Megarad of 40 MeV electron dose. While this is a larger change than the swept quartz devices, it is still much less than is typically exhibited by Si CMOS integrated circuits, even those with relatively good radiation hardness. The authors suggested that the frequency shifts were due to radiation-induced changes in the quartz surface material where the surface acoustic waves propagate through the crystal.

Recently, Taylor[99-100], et al have examined radiation effects on $PbMoO_4$ AO devices, and found in the first study that a transient x-ray pulse delivering 366 rads in 20 ns ($1.8 \times 10^{10}$ rads/sec) caused an induced attenuation of about 2.5 dB for the optical signal traversing the AO grating device. Exposures at relatively low total dose levels near 9 kilorads at low dose rates did not alter the properties of this AO grating.

Later studies[101-102] detected the pulsed radiation-induced shift in the Bragg diffracted optical beam from AO Bragg grating devices fabricated from $PbMoO_4$, $TeO_2$ and InP. Exposure of $PbMoO_4$ AO Bragg grating device to pulse trains of 15 MeV electrons from a LINAC demonstrated that the position of the diffracted optical beam shifts more and more with dose (15 to 386 kilorads) away from the pre-irradiation beam

position. These shift were attributed to radiation induced temperature increases in the active regions of the AO Bragg grating since measurements demonstrated that there was a significant temperature raise following the pulse train. Interestingly, the authors checked for temperature-induce changes in the Bragg angle, but found none. The authors also observed a decrease in defraction efficiency with increasing dose and this was attributed to the introduction of color centers. It is unfortunate that the effects of temperature could not be separated from other potential radiation effects such as the introduction of color centers. In future experiments, an attempt should be made to separate these effects.

Taylor[102], et al recently examined the effects of pulsed 15 MeV electrons and Co-60 gamma rays on a ferroelectric liquid crystal (FLC) light valve. This device was made up of glass cover plates enclosing the thin FLC layer. Transparent conducting coatings of indium-tin-oxide (ITO) were used as electrical conductors on the glass plates. Exposure of these FLC light valves to Co-60 irradiation up to a level of 67 kilorads showed no changes in characteristics of the FLC device. In contrast with these results, for electron exposure, permanent attenuation was observed at doses above 66 kilorads. No explanation was given for the difference in response to Co-60 and 15 MeV electrons. It was also noted that because the light valve could not be disassembled for radiation studies, the authors were not able to tell in which part of the device the radiation-induced attenuation occurred. The attenuation may have been due to darkening of the glass cover plates, since one does not expect changes in organic based liquid crystal materials at doses as low as 100 kilorads. This is supported by recent electron irradiation studies of dispersions of nematic liquid crystals in polymers.

### 3.4.4 Documented Research Status on Semiconductor Based Modulators.

3.4.4.1 Semiconductor Modulator Technology. A sampling of recent review articles[103-108] attests to the very rapid growth of the area of semiconductor-based modulator research and development. Our goal is to discuss those common features and trends in this very large array of devices that are relevant to radiation hardness of semiconductor modulators. Since hardly any radiation effects testing of semiconductor modulators has been performed, we will rely heavily on radiation effects studies of other types of semiconductor devices such as Si CMOS, GaAlAs LEDs and laser diodes and other III-V materials.

While Si-based devices, both analog and digital, and Si substrate materials, play an important role in the development of integrated semiconductor modulator and photonic device circuits, it is primarily a secondary role that is centered around attempts to integrate III-V photonic devices with standard Si technology. In addition, Si-based modulators have $SiO_2$ as the active waveguide and thus, the discussion of these modulators belongs in our previous section on insulator-based modulators. Actual modulator structures are fabricated almost entirely in III-V

materials and modulator structures and the radiation effects issues associated with these materials and devices.

An important feature of many types of semiconductor modulators is the requirement for fabrication of optical waveguides. As in the case of polymer and insulator-based devices, this is done by varying the refractive index in a controlled manner. In the III-V semiconductors, there are two methods for achieving the necessary variation in refractive index. The waveguide can be formed using either heterostructures of different materials, or homostructures in which the carrier density is varied in order to alter the refractive index. In the AlGaAs system, layers of varying Al content can be grown in order to fabricate waveguides with varying index. For $Al_xGa_{1-x}As$, the refractive index varies approximately linearly from $n \approx 3.57$ for $x = 0$ to $n \approx 3.36$ for $x = 0.35$ in the near infrared. Thus, a GaAs layer between two AlGaAs layers (double heterostructure) will form a waveguide. The AlGaAs system is particularly well-suited for this "band gap engineering" because GaAs and AlGaAs with moderate Al content have essentially the same lattice constant so that high material quality is maintained in complex layered structures. Similar waveguide structures can be fabricated in other III-V material systems, such as InGaAsP, although the lattice matching requirements are sometimes more restrictive than for AlGaAs. Several representative semiconductor modulator types are discussed below.

A transverse electro-absorption modulator is an AlGaAs/GaAs P-I-N diode with the multiple quantum well (MQW) structure embedded in the *i*-region of the diode. The optical signal beam impinges on the top of the modulator and passes through the diode in a transverse manner perpendicular to the MQW layers. This configuration makes the device attractive for SLM applications where a matrix of light beams impinge on a grid of such devices. The electric field is applied in the same direction in order to achieve quantum confined Stark effect (QCSE). With no bias applied, the light beam passes through the structure with little attenuation. Upon the application of bias, the absorption shifts to lower energies so that the light beam is absorbed, achieving the intensity modulation of the beam. These devices are very fast because their internal response is limited only by the carrier tunneling times required to remove carriers from the wells, and these times are on the order of 10 to 100 ps, implying possible modulation bandwidths of 50 to 100 GHz. Devices have been reported with impulse responses of 131 ps. The overall response of these modulators is determined by the RC time constant of the circuit in which the modulator is placed. If the capacitance can be limited to a few tenths of a pF, then bandwidths of 10s of GHz are possible.

Another important feature of these modulators is the extinction ratio, or on-off ratio; that is, the ratio of transmitted light beam intensity when the device is on to that when it is off. This ratio depends on the extent of the exciton absorption shift induced by the application of the electric field. This ratio increases rapidly with decreasing temperature as the exciton absorption resonance narrows and becomes stronger. However, at room temperature it is difficult to achieve a large extinction

ratio. One solution to this is to construct the transverse modulator as a reflection modulator so that the beam passes throughout the MQWs twice. This can be accomplished by depositing a metal reflector at the substrate side of the device, or by using a quarter-wave multilayer dielectric mirror below the MQWs. This structure has the added advantage of not having to remove the substrate, which is required in the non-reflection configuration so the beam can pass entirely through the device without attenuation in a thick GaAs substrate.

If we change the configuration of the P-I-N diode electro-absorption modulator discussed above so that the MQW layers form a waveguide and the light is injected into the waveguide parallel to the MQW planes, we have an electro-optic MQW modulator that can be coupled to fibers and used in a communication system. In these bulk materials, the EO effect is small compared with $LiNbO_3$ and other materials. However, if the waveguide is formed from MQWs, then not only the linear EO effect is present, but also the quadratic EO effect due to the QCSE on the refractive index, by way of the Kramers-Kronig relationship. In this type of modulator, the light wavelength must be chosen near the exciton resonance since the QCSE is an exciton effect. It can be shown that the refractive index depends on the square of the electric field for the QCSE, and this provides the extra sensitivity that makes these modulators attractive. It has also been shown that the electro-optic effect can be enhanced further by introducing strained layer, lattice mismatched quantum wells. The sensitivity of the refractive index to electric field has led to efficient phase modulators in which a 520°/V-mm phase shift has been observed. These devices also operate in the 10s of GHz modulation speed range. With regard to radiation effects, it is important to take into account any type of irradiation, such as neutron exposure, that will affect the near-edge absorption spectrum.

A particularly important application of this class of modulators is the external modulation of high speed lasers used in communications systems. Lasers combined the external modulators on the same chip are available commercially. The use of external modulators avoids the frequency chirping effect exhibited by many lasers when modulated at high frequencies. This chirping effect can significantly reduce the bandwidth of a communication system. The ability to fabricate lasers and modulators on the same chip is due largely to the advent of selective area epitaxial growth techniques in which layers of different thickness and material sequence can be grown on the same substrate. Such techniques are largely responsible for integration of many types of devices on a single substrate in the III-V materials families.

In a total reflection switch/modulator device, two intersection waveguides made up of MQWs allow total internal reflection to occur at the intersection of the waveguides in such a manner that the light beam can be switched from one output waveguide to the other. The electric field-induced QCSE is used to control the reflectivity of the intersection planes so that total internal reflection occurs at a certain applied bias, but not at zero bias where the light beam passes straight through the device in the waveguide in which it was launched. A particularly important

feature of this device is that its operation is independent of the polarization of the input beam so that polarization fluctuations often seen in fiber transmission to not affect its operation. The total reflection switch is relatively simple to construct and matrix switch arrays are easily fabricated.

Direction couplers similar to those discussed earlier fabricated from $LiNbO_3$ have also been reported in a variety of III-V materials. Most of the devices reported were made in bulk heterostructures rather than MQW waveguides. While these devices are not as sensitive as LiNbO3 couplers, because of the smaller EO coefficients, they have the significant advantage of being easily integrated with other photonic devices on III-V substrates. More recently, vertical MQW direction couplers have been fabricated in both GaAs/AlGaAs and GaInAs/InP materials structures. In these devices, the waveguides actually lie on top of each other so that coupler occurs vertically between the guides. The increased sensitivity due to the QCSE allowed the use of very short device lengths, approximately 170 µm.

In GaAs/AlGaAs structures it is possible to achieve refractive index changes by optically altering the carrier density in a waveguide by altering a built-in electric field that exists in a waveguide. Optical excitation of electrons from the valence band to the conduction band fills the low states in the conduction band minima, a process termed band filling, and results in a change in the near-band edge absorption coefficient. Thus, it is also possible to optically alter the absorption of the signal beam by modifying the absorption in the waveguide. Using these optically induced effects, one can construct an all-optical modulator using a signal beam and a second control beam that changes the refractive index in each signal beam optical path. The control beam can be orthogonal to the signal beam, or be parallel to it with a different polarization in order to keep the beams separate. Modulation depths greater than 8 dB have been observed using a control beam in the mW range. As in other carrier-induced modulation schemes, the speed of these modulators is limited by the minority carrier lifetime. It is interesting to note that ion implantation has been used to purposely reduce the lifetime to the picosecond range so the resultant modulator has greater bandwidth. Thus, as we noted earlier, one might anticipate that radiation would actually improve the operation of these devices.

3.4.4.2 Radiation Effects on Semiconductor Modulators. Although III-V semiconductor modulator structures present an interesting challenge with regard to radiation effects, we note that essentially no radiation effects have been performed directly on these types of devices. Three features of III-V modulators suggest that these devices will have a broader, more varied response to irradiation than polymer or insulator-based modulators. III-V modulator structures take advantage of the variation of the absorption edge with electric field, in particular the absorption governed by exciton behavior in quantum wells. It is well known that irradiation can affect the absorption edge of III-V materials. In many of these structures we find a diode structure with an i region that has an electric field across it. Such a structure will be particularly sensitive to transient upset caused by large radiation-induced photocurrent pulses. Many semiconductor modulator structures contain some type

of transistor, such as an HBT phototransistor, that increases the gain of the device. These devices will be sensitive to permanent damage of the type that affects the minority carrier lifetime. Thus, it should not be surprising if the response of III-V semiconductor modulators to radiation reveals several interesting and significant effects.

Fortunately, there have been a variety of radiation effects studies of other types of III-V electronic and photonic devices and materials. It should be possible, at least in part, to infer the effects of radiation on modulator structures based on these studies of III-V materials and other device types. In the recent literature, these include radiation effects in GaAs MESFETs[109-112], GaAs MMICs[113], HBTs and HEMTs[114-116], GaAs diodes[117], solar cells[118], electrical properties of GaAs[119], optical properties of GaAs and GaP[120-121], and various photonic devices (photodiodes, lasers, quantum well lasers and LEDs)[122-125]. Certain general comments can be made that are derived from this body of work which are relevant to the issue of radiation effects in semiconductor modulators.

Neutron irradiation studies[114] of high electron mobility transistors (HEMTs) have revealed that these devices are surprisingly resistant to irradiation. Although a neutron fluence of approximately $10^{14}$ n/cm$^2$ causes a significant reduction in electron mobility (about a factor of 4), the transconductance of the HEMT does not decrease much because the carriers are in velocity saturation. Thus, although the undoped GaAs wells in which the electrons move are relatively pristine because of a lack of dopant atoms that can act as scattering centers, these devices are not particularly susceptible to displacement damage. Therefore, a delta-doped MQW lateral field modulator will be more resistant to irradiation than one might expect.

It has been known for some time that neutron-induced displacement damage in GaAs and AlGaAs has unique features compared with point defects generated by electrons and protons[126]. In particular, neutron irradiation causes a broad smearing of the absorption edge with significantly greater absorption at photon energies well below the bandgap energy. This general result suggests that modulators that depend on electric field-induced changes in exciton absorption (QCSE) to achieve modulation may be strongly affected by neutron irradiation. These effects would be accentuated in those modulators constructed so that the light beam makes multiple passes through the MQW region (Fabry-Perot and reflection modulators).

With regard to ionizing radiation effects (total ionizing dose: TID) in GaAs, this material is much more resistant than standard Si CMOS circuits. This is because the $SiO_2$ gate and field oxides in Si devices are very susceptible to ionization-induced changes caused by trapping of holes and interface state creation at $SiO_2$/Si interfaces. Essentially, there is no analogous effect in GaAs/AlGaAs devices and TID effects are not usually a problem in III-V devices. Thus, in photonic systems total dose effects are usually considered only for the optical fiber portion and any Si digital or analog signal processing electronics in the system.

Since the minority carrier lifetime in GaAs is typically short (10s of nanoseconds compared to 10s to 100s of microseconds in Si), displacement damage-induced reductions in minority carrier lifetime are not as much of a problem in GaAs devices, such as LEDs, laser diodes, solar cells and bipolar transistors, that depend on minority carrier lifetime for their successful operation (this is why GaAs solar cells resist irradiation much better than Si solar cells). However, many studies[127-133] have shown that LEDs and laser diodes can experience significant degradation in light output at neutron fluences below $10^{14}$ n/cm$^2$. Thus, in transistors-self electro-optic effect device (T-SEED) modulators, for example, that contain phototransistors that provide gain, device degradation may occur at neutron(or proton) fluences that are near or below military requirements. In contrast, as we have noted above, in those modulators whose switching time is limited by carrier lifetime, irradiation may actually improve device performance.

## 3.5 DOCUMENTED RESEARCH STATUS ON OPTICAL FIBERS.

The general issues associated with ionizing radiation damage in optical fibers, whether permanent or transient, relate to the induced attenuation caused by light absorption or displacement damage. The basic ionizing energies are in the forms of particles (alpha, beta, proton, electron, and neutron) and high energy electromagnetic waves (x-ray and gamma rays). Any of these forms of ionizing energies may be capable of inducing losses in optical fibers, assuming sufficient energy and flux (rads per unit time). These particles or electromagnetic waves may affect the optical characteristics of the fiber such as its absorption, scattering and index of refraction properties. Because of the nature of optical fibers, induced absorption is usually expressed in dB/km rather than as cm$^{-1}$, which is usually the case for absorption coefficients.

Ionizing radiation induced attenuation in an optical fiber is caused by the loss or reduction of the optical signal from two mechanisms: scattering and absorption[134-136]. The ratio between the index of refraction of the fiber core and cladding ensures that the light ray entering the fiber end will experience total internal reflection at the core-cladding interface as it propagates down the fiber. The scattering mechanisms do not influence radiation effects in optical fibers or are unusually minute compared to the absorption phenomena. Any change in the refractive indices is also believed to have a minute effect on fiber performance. However, the scattering effects and the numerical aperture do influence the overall selection of currently available optical fibers. In recent years, the purity and fabrication of commercial fibers have reached the point where fiber attenuation has been optimized to the scattering limit which obviates the desire for longer wavelength, low loss fibers.

From the point of view of ionizing radiation induced effects, it is possible to identify two principle interactions of ionizing radiation with the optical fiber. The ionization of electrons, which relates to the absorption of light in the core of the

fiber by various types of color centers, is the most common damage mechanism in fibers. The other damage mechanism is the direct displacement of atoms by elastic scattering.

In fibers, the electrons and holes produced by the ionizing radiation can subsequently be trapped at the pre-existing flaws or dangling bonds in the fiber structure to produce a defect center (color center). Pre-existing flaws arise because of the presence of both substitutional or interstitial impurities or dopants; the lack of stoichiometry in the glass structure; multivalent cations present in the glass; and highly strained bonds due to the fabrication process of the fiber.

We have stated that ionizing radiation creates broken and dangling bonds which act as charge trapping sites in optical fibers. We also noted that the addition of dopants can strongly impact the defect center production and charge trapping process. Finally, we indicated that pre-existing flaws and strains caused by preform fabrication and fiber drawing are common in fibers and are therefore more susceptible to ionizing radiation than the bulk materials. These defect centers typically possess ground state energy levels between the conduction and valence bands which result in the formation of both optical absorption and luminescence bands in the uv, visible, and ir spectral regions. The contributions of optical absorption from several different defect centers affect any given wavelength. This issue is further complicated by the fact that these color centers are not all permanent so that some recovery and annealing of absorption is observed in some materials while continual damage occurs in other materials after ionizing radiation has ceased.

Since most of the collected documentation relate to optical fiber testing, we have a significant distribution of data in this area. Figure 3-15 provides a graphical distribution of the documents that have been published or acquired over the past decade plus. Over 180 documents have addressed radiation testing of optical fibers which would include single mode, multimode, graded index and polarization maintaining fibers. A number of papers were collected from the early 80's, but the most recent documents which were published between January 1992 and May 1995 comprise the largest accumulation of our data set. Figure 3-16 provides a more detailed breakout of each time period by radiation test environments. It can be seen that total dose testing dominates this component classification. It is also evident that little or no proton testing took place prior to 1990. With the increased emphasis on survivable fiber optic systems on spacecraft, fiber testing has been progressing over the past 5 years. Neutron testing was important prior to 1986 when the military community was developing nuclear survivable systems. More recent neutron tests support nuclear power plant instrumentation and control system designs. Figures 3-17 to 3-20 provide a summary of each environment and the distribution of documentation over our ten year plus data collection time frame.

Figure 3-21 separates the collected documents into each environment and further divides this data into operating wavelength measurements. Predominately, most tests were conducted at specific data transmission wavelengths with only a few broadband exceptions. In the total dose environment, most of the tests were conducted at the shorter wavelengths (850 nm and 1300 nm). A little over 10% of the tests were conducted at 1550 nm. It is also easy to see the transition of a researcher's test schedule over time by observing the operating wavelengths for each test. Most of the 850 nm tests were performed in the early 80s with a shift to 1300 nm tests in the mid to late 80s. Most of the 1550 nm tests were conducted in the past several years. This is typical for all four radiation environments. The prompt transient tests were also performed at 850 nm in the early 80s, and the 1550 nm were more recent. The proton tests were consistently at the longer wavelengths, since most of this testing has been performed in the past five years.

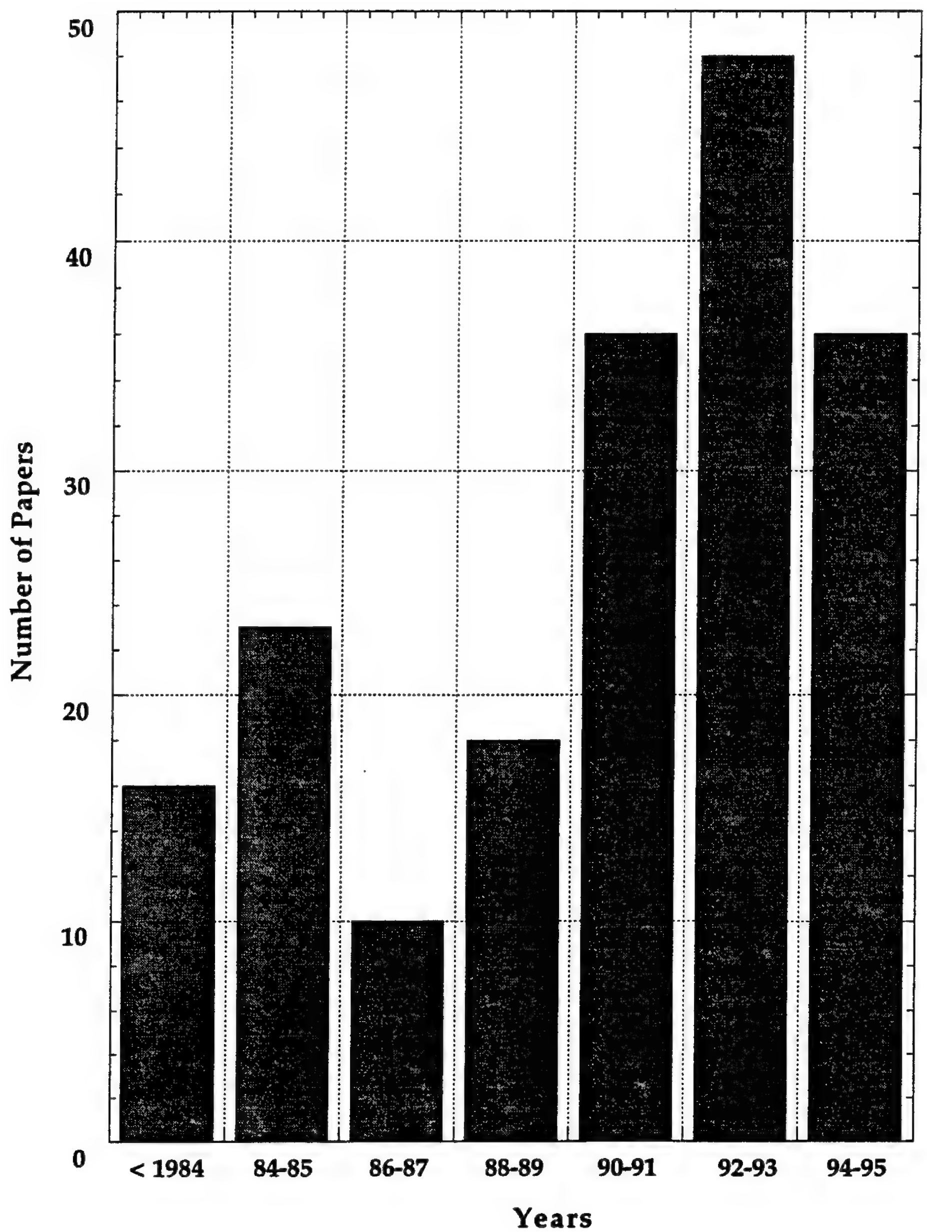


Figure 3-15. Number of papers over time for optical fibers for all radiation environments.

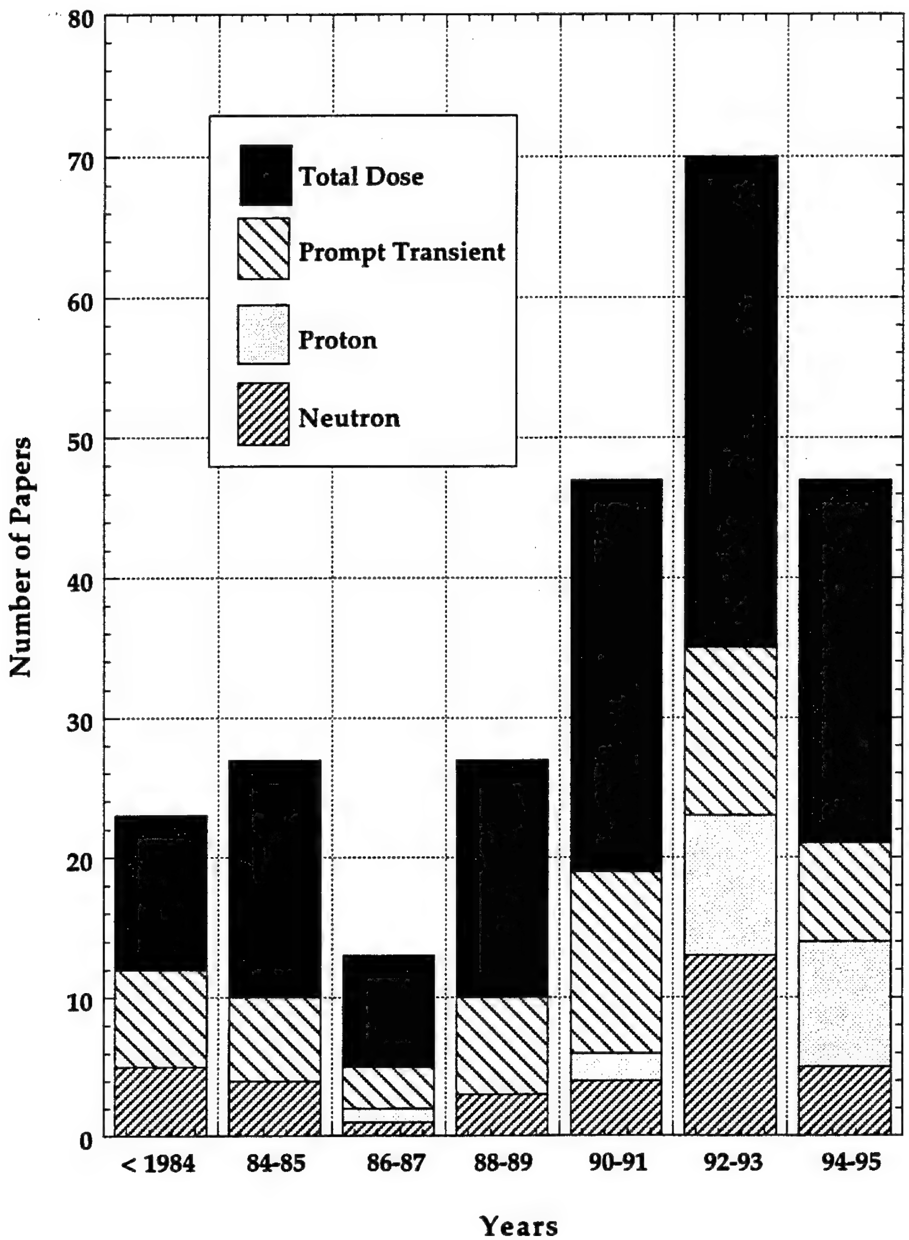


Figure 3-16. Number of papers over time for optical fibers for each radiation environment.

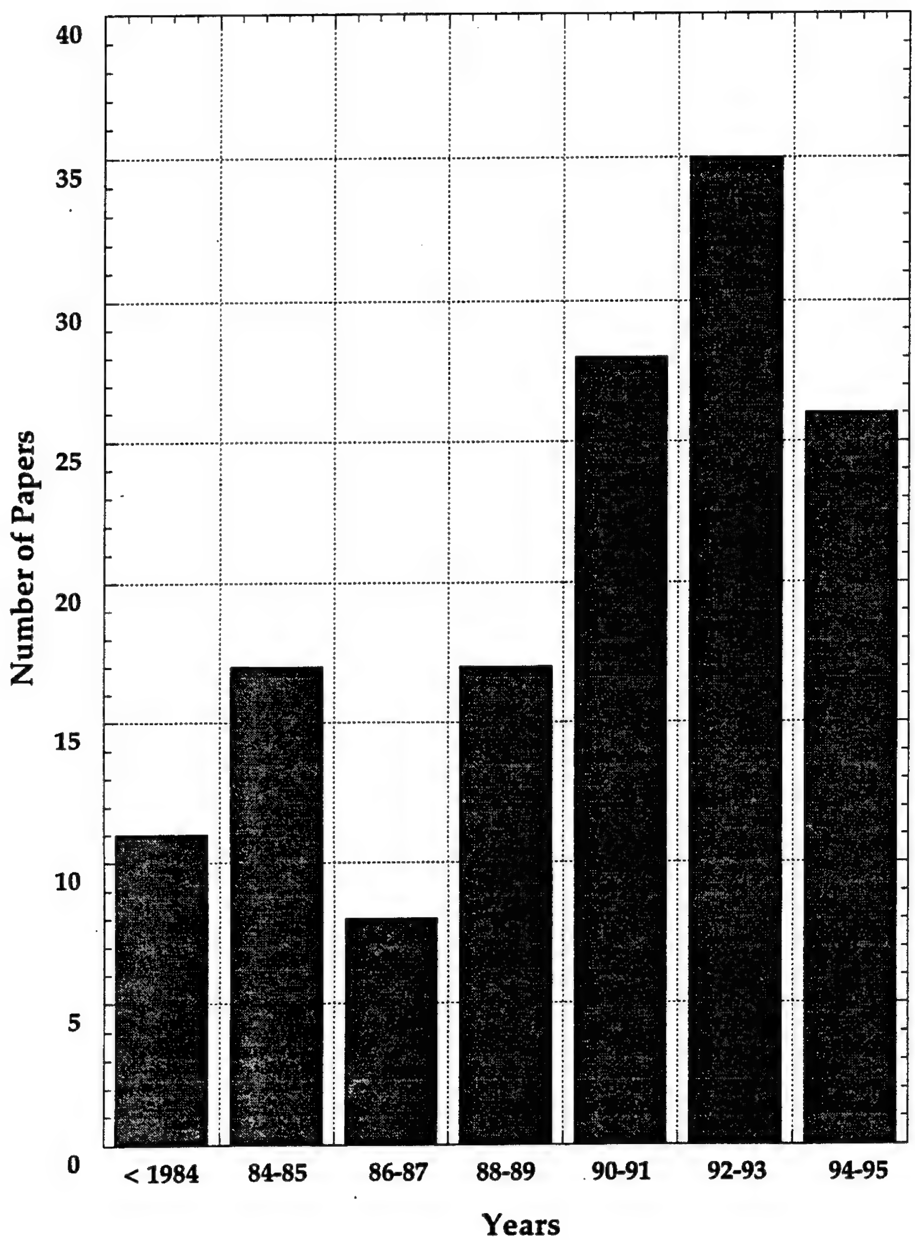


Figure 3-17. Number of papers over time for optical fibers tested in a total dose radiation environment.

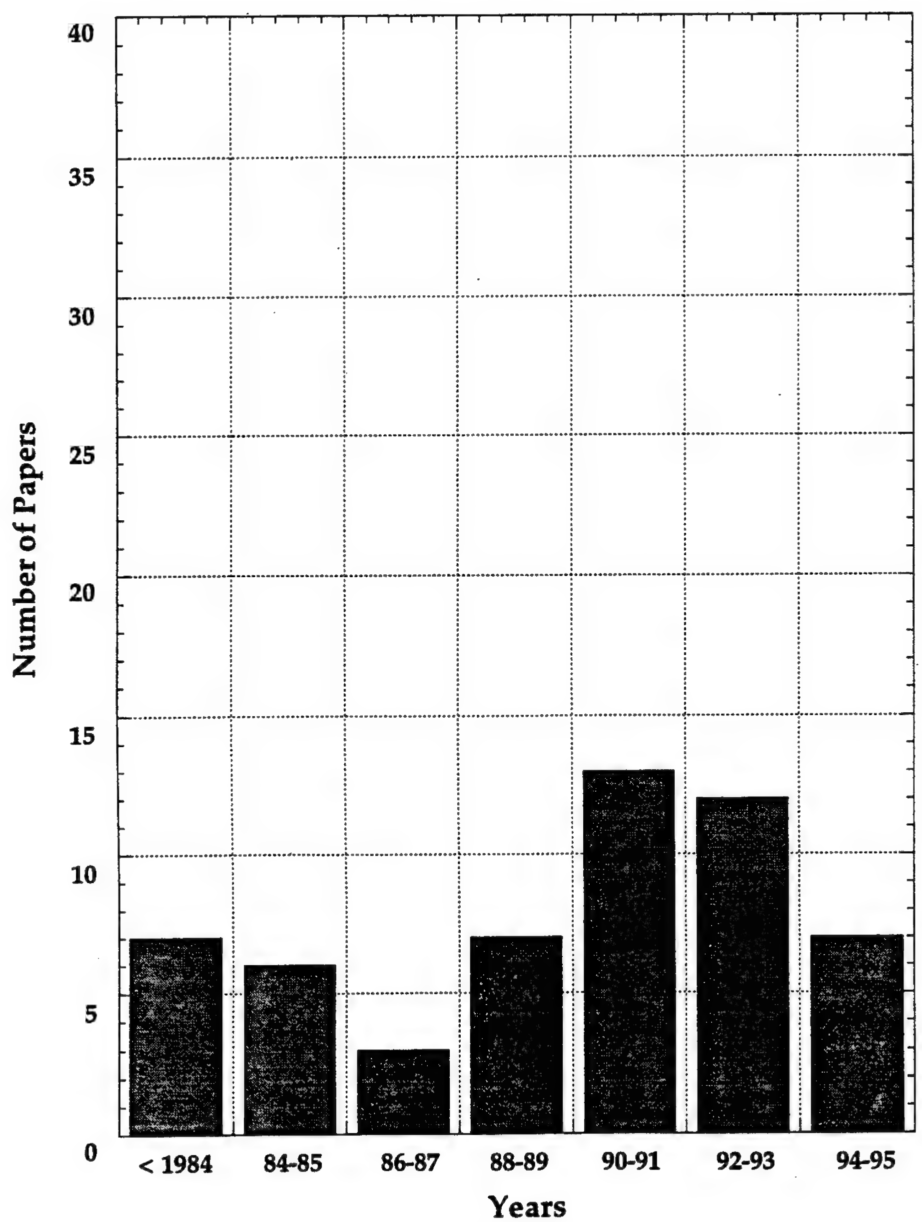


Figure 3-18. Number of papers over time for optical fibers tested in a prompt transient radiation environment.

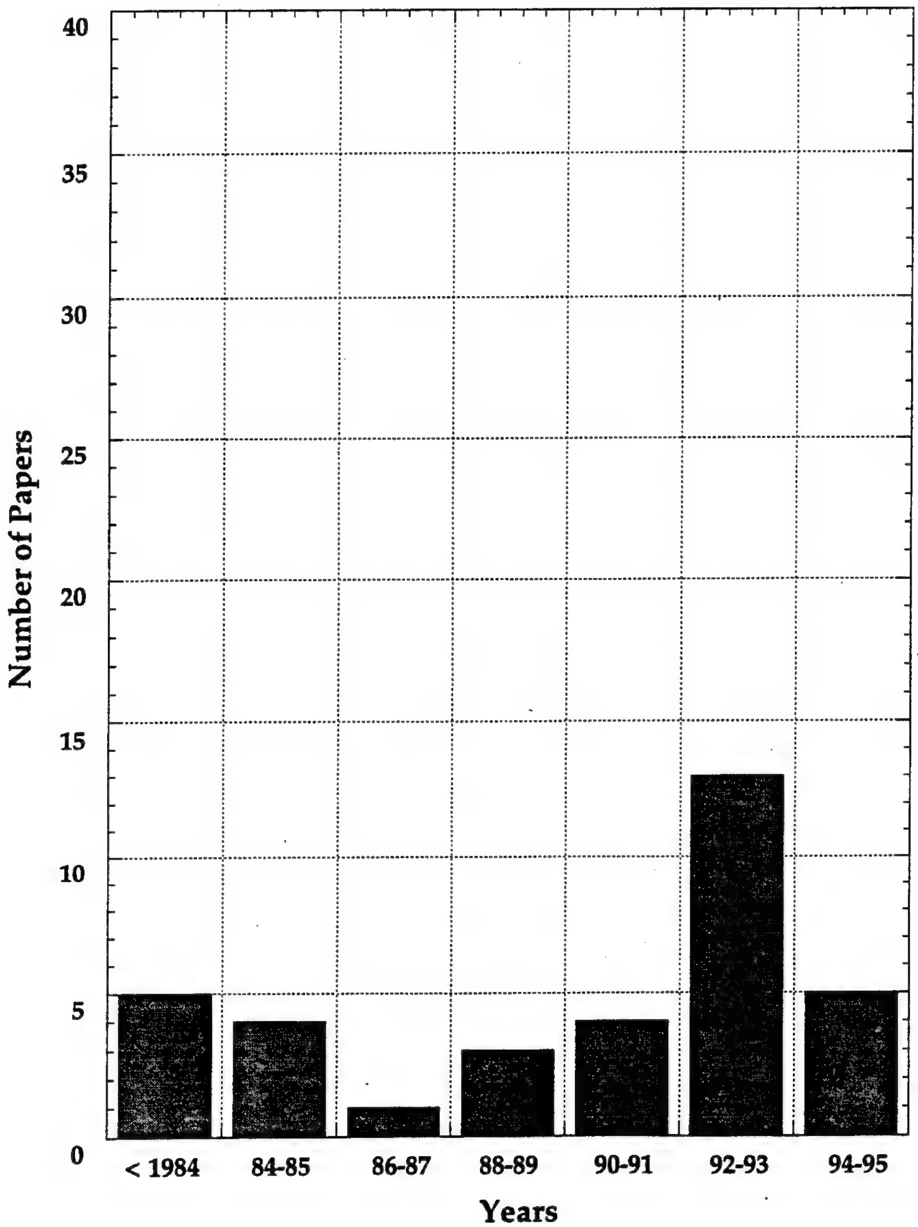


Figure 3-19. Number of papers over time for optical fibers tested in a neutron radiation environment.

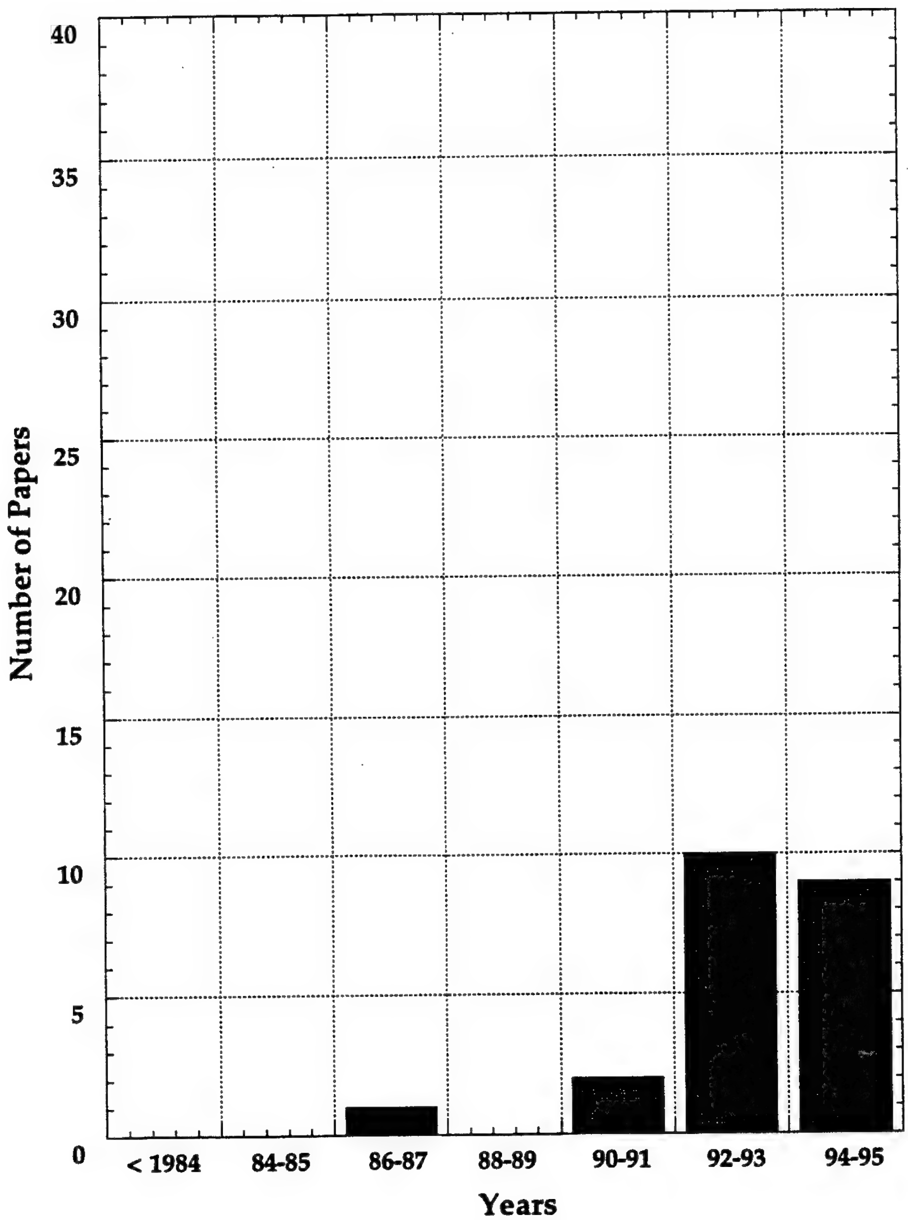


Figure 3-20. Number of papers over time for optical fibers tested in a proton radiation environment.

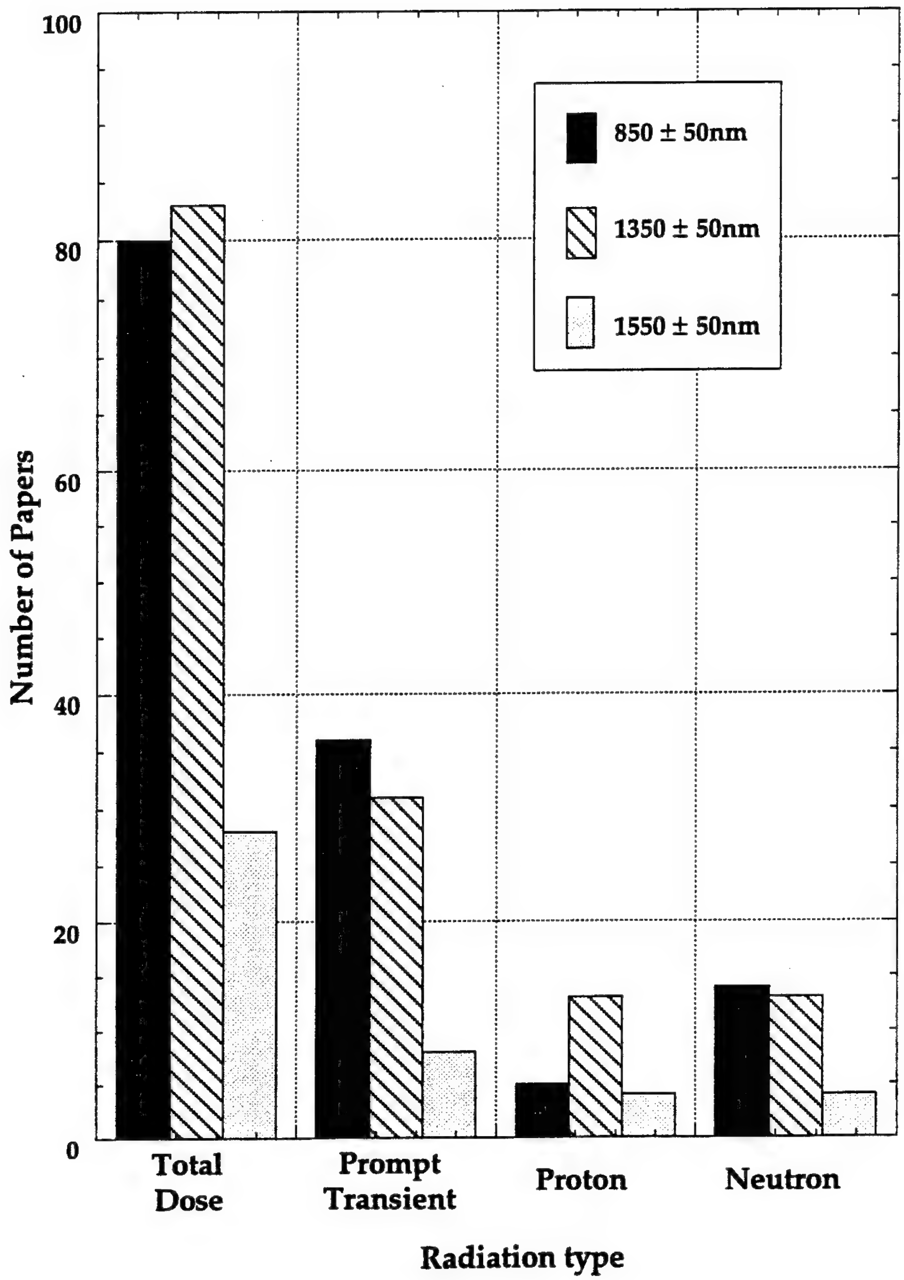


Figure 3-21. Wavelength distribution for optical fiber testing for each radiation environment.

Figure 3-22 presents a graphical characterization of the number of parameters that must be considered while performing radiation tests. Most radiation testing of optical fibers has been performed in accordance with specific system requirements, at research facilities with equipment or facility limitations, or in accordance with round robin testing guidelines developed by the NATO Nuclear Effects Task Group. Past testing has demonstrated that the radiation induced loss in optical fibers is primarily dependent on operating wavelength, temperature, optical power and total dose as well as various other test conditions. This complex set of test conditions is shown in the figure and attempts to graphically portray the intricacy of these tests. Figure 3-23 shows one of the test parameters and the range that this one test condition can vary. Temperatures as low as -193 Celsius and as high as +320 Celsius spread the gamut of temperature tests. Most of the tests have been performed at room temperature and the majority of the tests fall within a 50 degree range. Military systems require that tests be performed over a given temperate range which justifies some of the range of temperatures where tests have been performed. Many facilities do not have access to a temperature chamber which is why the majority of the tests are performed at room temperature. Figure 3-24 demonstrates another test parameter which ties total dose to dose rate. The variety of dots represent test points while the large bullets and symbols represent required test levels. It can be seen from this figure that out of the 108 documented test results only 24 comply with either the EIA/TIA FOTP-64[137] radiation test procedure or the ASTM E1614-94 radiation test procedure. It is evident for these two parameters that there exists very little consistent data for review and analysis.

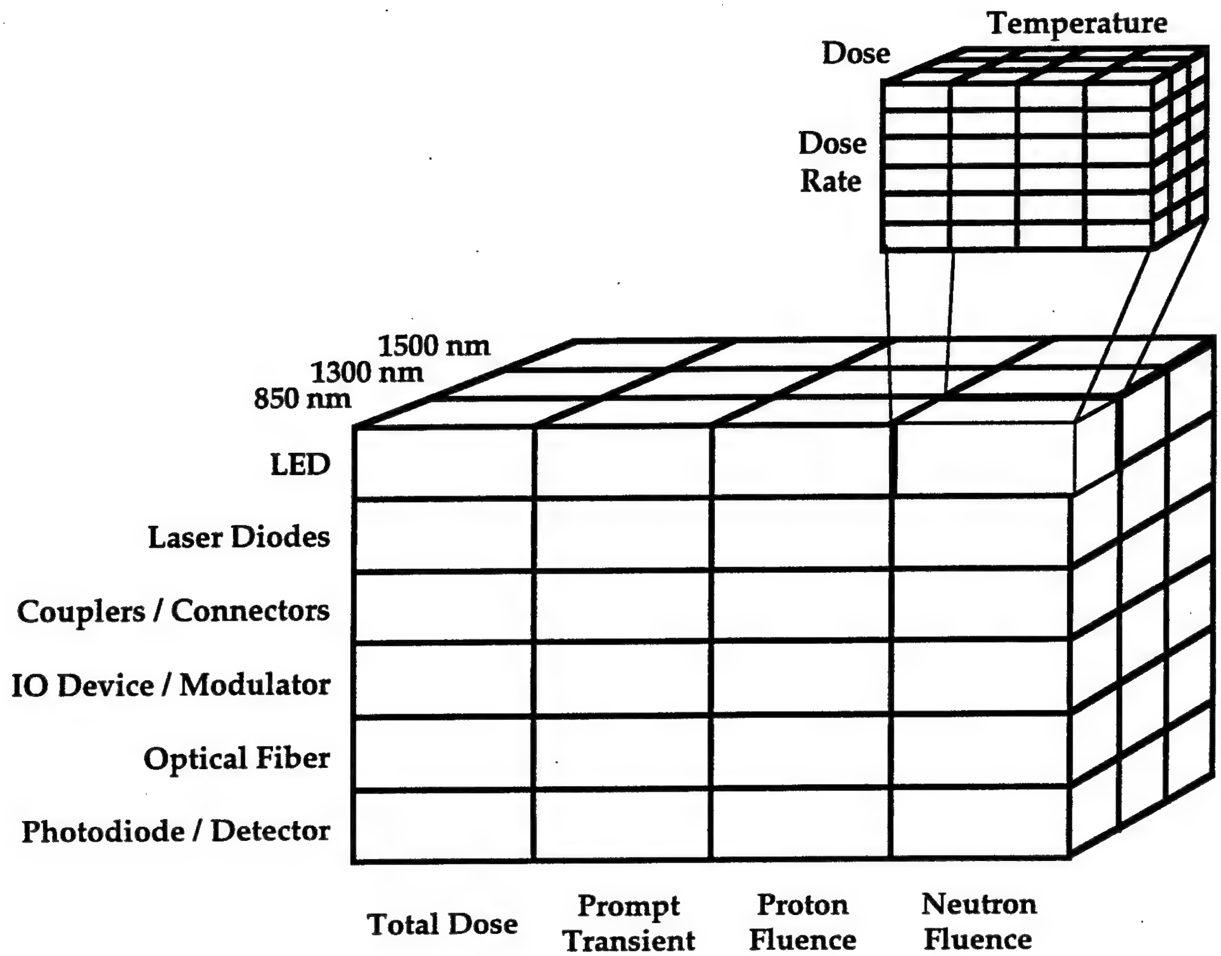


Figure 3-22. Radiation test parameters.

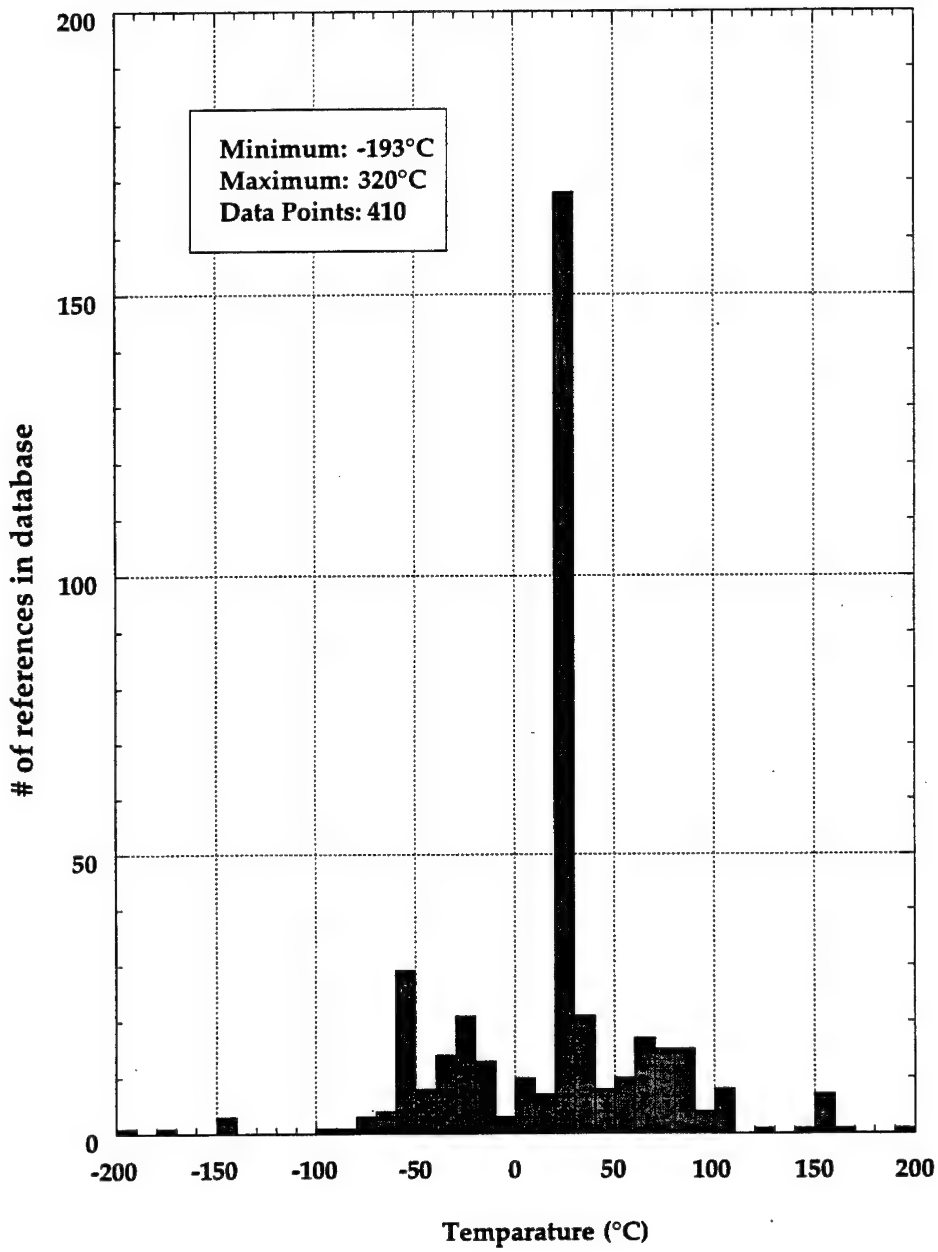


Figure 3-23. Temperatures of interest for all radiation testing.

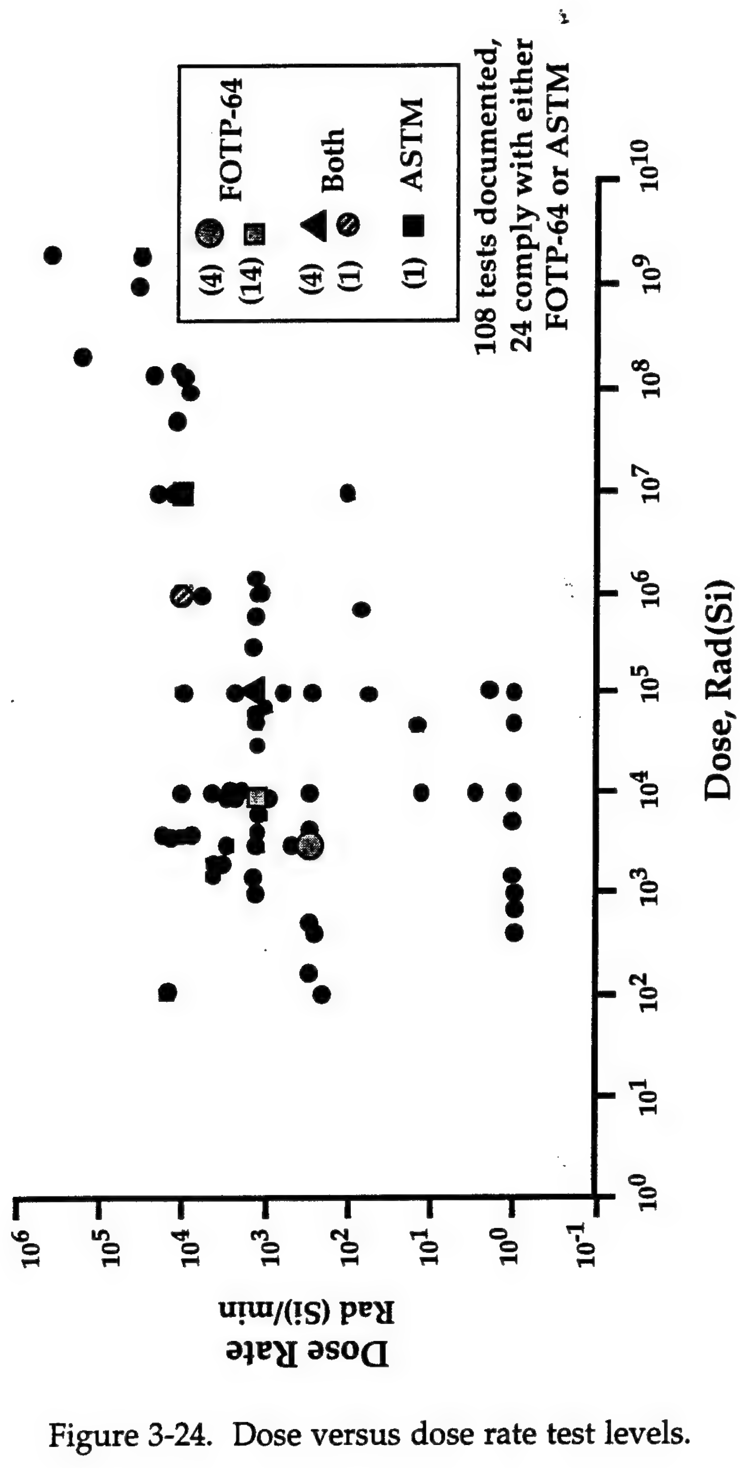


Figure 3-24. Dose versus dose rate test levels.

## 3.6 DOCUMENTED RESEARCH STATUS ON DETECTORS.

At the other end of the fiber is the optical receiver which converts the optical energy back into electrical energy. This electrical energy is in the form of an electrical signal which is typically compatible with the existing electrical equipment, computer and/or communications gear. The optical detector or photodiode absorbs light very strongly at the wavelength of the optical input signal. Two key types of semiconductor photodetectors have been used in fiber optic systems, a PIN photodiode and an avalanche photodetector (APD). The avalanche photodetector is more efficient across a wider spectrum and experiences less interference than the simpler PIN photodiode. In the design of either, the thick intrinsic substrate offers a high efficiency of photon-to-carrier conversion while a thin layer is required to increase optical signal responsivity. The thick layer increases the probability of incident photons creating electron-hole pairs in the depletion region, and a thin layer reduces transit time of the carriers swept across the depletion region. Operational performance alone requires that an optimized design of the substrate take into account the balance between efficiency and optical responsivity.

There is a significant variety of detector types to include P-N junction photodiodes, P-I-N photodiodes, phototransistors, avalanche photodiodes[138]. They are fabricated from a variety of materials (Si, Ge, various III-V's like InGaAsP). All of these device types fall within the classification of semiconductor photodetectors. In a broadband system the detector may either be an array of photodiode or a charged coupled device (CCD)[139-140].

As a vehicle for delineating radiation sensitive properties, we begin our discussion with a consideration of the relatively simple Si P-N junction photodiode, which is similar in behavior to a solar cell. The P-N junction photodiode is typically asymmetrically doped, for example as $N^+$-P, with the thin and heavily doped layer exposed to the light signal. Because of surface recombination and the short hole diffusion length in the thin $N^+$ region, it is usually assumed that this region does not make a significant contribution to the photocurrent. Since the P region is relatively lightly doped, the space charge region will be significant over the range including the space charge region and approximately one to two diffusion lengths into the P-region.

Hardening of photodiodes by minimizing diffusion limited collection and maximizing collection within the depletion region also introduces the need for compromise because a wide depletion region requires that the Si in this region be lightly doped (we will indicate below that this compromise is not nearly as severe for III-V based photodiodes). Under such conditions, neutron irradiation can lead to carrier removal and mobility degradation leading to increases in series resistance at relatively low fluences (although not as low a fluences that will significantly reduce the minority carrier lifetime). A recent study by Korde, has shown that significant

increases in series resistance can occur above $10^{12}$ n/cm $^2$ fluence levels, and that these changes affect the linearity of the photodiode.

Detector structure whose responsivity does not depend on diffusion-limited collection of photogenerated carriers are not, however, completely immune to radiation damage degradation. Previous studies have shown that irradiation-induced leakage (dark) currents are observable at neutron fluences that do not necessarily affect the responsivity. These dark currents result from radiation-induced increases in the bulk density of non-radiative recombination centers in the depletion region, and from radiation-induced surface effects. Lattice damage-induced increase in dark current also leads to changes in the shunt resistance of photodiodes. Neutron irradiation can also change the C-V characteristics of photodiodes which will affect their speed performance.

While the above comments on lattice damage effects in detectors indicate that one can avoid many radiation susceptibility problems by using P-I-N photodiodes, the issue of ionization effects in detectors is much more difficult. This is not particularly surprising since photodetectors are specifically designed to efficiently convert electromagnetic energy, whether a 1.3 micron signal photon or a high energy gamma ray, into electrical current. Indeed, in those fiber optic links where the fiber is relatively short, ionization-induced photocurrents in the photodiode can be the most severe radiation effects problem for the entire link.

Because the same physical process is responsible for creating photocurrent in a photodiode for both the light signal and for high energy ionizing radiation, one cannot depend on a separation of different physical processes to eliminate or minimize ionization-induced photocurrents. Although the generation process is common to both types of photocurrents, the regions of the device in which each type of photocurrent is produced are not entirely the same. While highly energetic gamma ray protons and x-rays generate electron-hole pairs uniformly throughout the semiconductor material of the photodiode, the optical signal generates carriers only in the active region, which is equal to the P-N junction depletion layer width plus about one minority carrier diffusion length on either side of this layer. Note that for a Si P-I-N photodiode with a wide intrinsic region, which we have shown is least susceptible to lattice damage, these two regions nearly coincide since nearly all of the device is optically active. Recent work has shown that ionizing radiation hardening can be achieved by: (1) minimizing the volume of the active region of the photodiode without sacrificing the responsivity of the device to the optical signal, and (2) minimizing the volume of optically "dead" regions in the photodiode, and collection at the junction of radiation-induced carriers from these regions.

In order to accomplish the first goal, the photodiode must be fabricated from a semiconductor material which absorbs light very strongly at the wavelength of the optical signal. When the absorption coefficient is large the absorption length (defined as the thickness of material required to reduce the optical signal strength by

a factor of 1/e) is short so that the active region can be made thin without reducing the responsivity. The absorption coefficient of a semiconductor is determined by the energy band structure of the material with indirect energy gap materials such as Si having small absorption coefficients and direct gap materials such as GaAs having large absorption coefficients. It is for this reason that the active regions of typical Si photodiodes are quite thick, as much as 100 to 200 microns in a P-I-N photodiode. Thus, the necessity of having such thick active regions to achieve good responsivity also results in very large radiation-induced photocurrents. In contrast, satisfactory responsivities can be obtained in GaAs with active region thicknesses of only about one micron. It is important to note that a large absorption coefficient is a property shared by many binary, ternary and quaternary III-V semiconductors. Thus, photodiodes for all wavelengths relevant to fiber optic systems can be fabricated with appropriately thin active regions

In analyzing the documentation for the detectors, it was observed that there was significant interest in survivable devices prior to 1984 and a resurgence in more recent years. Most of the testing prior to 1984 revolved around survivable components for military systems. More recent studies are focused on survivable spacecraft systems. Figure 3-25 provides a representation of the distribution of the collected documents for the past decade plus. These tests were performed in all radiation environments and include the specific components such as PIN or APD as well as the complete receiver device with the PIN or APD incorporated into the test package. The detector array or CCD is also included in this documented research classification. Figure 3-26 has separated the environments as well as the operating wavelength at which the tests were conducted. It can be noted that most of the total dose tests were performed at either 850 nm or 1300 nm with some interest at 1550 nm. In proton and prompt transient tests documents, research was undertaken primarily at 1300 nm with interest at 850 nm and at 1550 nm. Typically the 850 nm tests were performed earlier in the decade, while the 1550 nm tests were performed in recent years. Most of the earlier device tests that were performed at 850 nm were under the auspices of Sandia National Labs. and were performed in the late 1970's and early 1980's. The 1300 nm and 1550 nm tests were primarily performed by NRL with a focus on survivable spacecraft systems. These research efforts were undertaken over the past 3 years and primarily address CCDs.

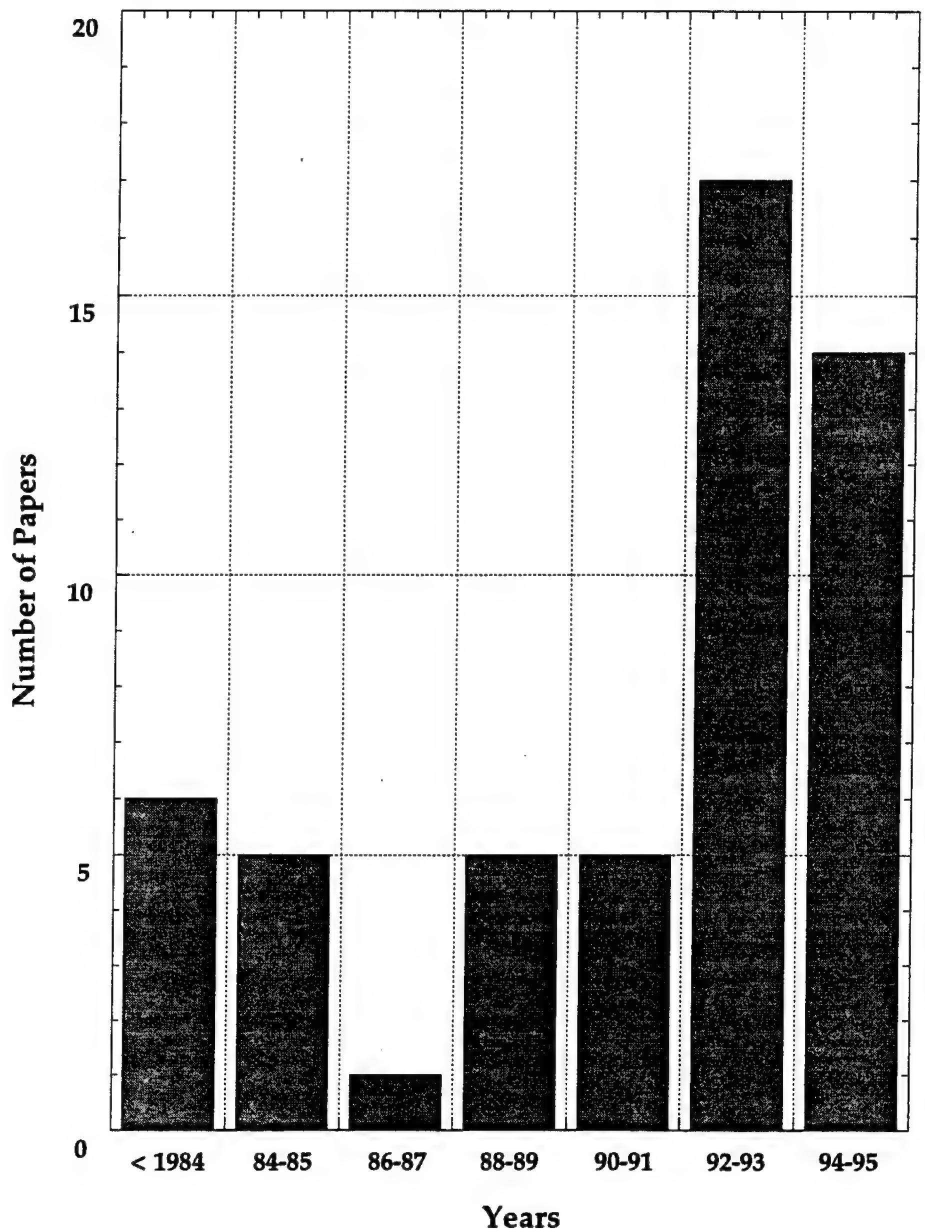


Figure 3-25. Number of papers over time for detectors in all radiation environments.

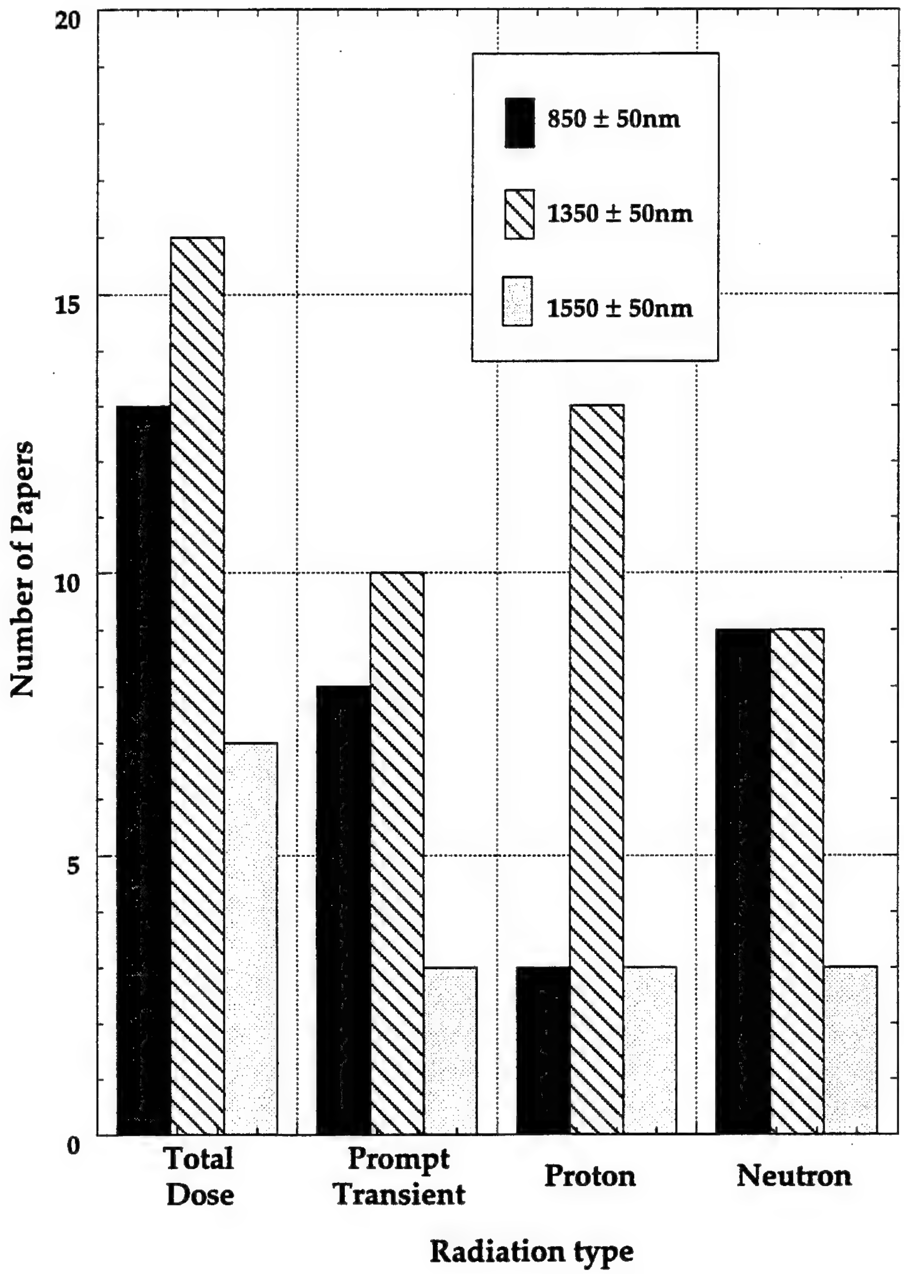


Figure 3-26. Wavelength distribution for detector testing for each radiation environment.

SECTION 4

# CONCLUSIONS AND RECOMMENDATIONS

## 4.1 CONCLUSIONS.

Significant progress has been made in identifying, delineating and standardizing radiation induced effects in optical fibers and components. To a much lesser extent, radiation induced effects in integrated optic guided wave structures have recently been the focus of a highly coordinated international round robin investigation. The AFMC Phillips Laboratory has supported the DNA photonics program by investigating and reporting the results of radiation induced effects in passive and active SLMs[45], IO[25-33] and AO devices[41-44]. These first results, and the confirmation and new findings of other experimenters[34-40], indicate that the responses of many photonic devices, both dated and new, are largely unknown and require continued and coordinated study to address and support space, nuclear weapons and environmental requirements and applications. Application of the photonics radiation effects and hardening data base is transitioning to the space environment or to addressing nuclear waste and contamination concerns. Highly coordinated research is required to compensate for the decrease in traditional funding appropriated towards radiation effects research. While the funding allocations towards this end have dwindled, the requirement for hardening technology may be greater than ever.

Table 4-1 provides a summary of the documented research efforts in the area of radiation effects in photonic components. The matrix is divided by component classes and environment categories. Within each block of the matrix, a notation is made as to the quality or status of the prior studies and the priority level for future studies. For example, this matrix shows that there exists an extensive amount of study and test results for optical fibers in the total dose and prompt transient environments. The requirement to perform future studies on optical fibers or other passive optical components such as couplers and connectors is minimal. In another region of the matrix, it is apparent that data on modulators is incomplete and that there is an urgent need to perform additional studies. The completeness of the data may relate to the amount of testing or the inconsistency in the test results from multiple facilities. Future test efforts should address all environments and should focus on various types of IO modulator components.

As work progresses in the qualification of polymer-based materials and devices for application in radiation environments, there should be clear separation between natural space environment applications and requirements, and applications intended for other nuclear related environments. This is necessary because the

latter environments will clearly be more difficult to satisfy. Dose rate and survivability requirements at very high dose rate levels may be difficult to meet, while the natural space environment does not include these highly stressing requirements.

Table 4-1. Summary of documented research.

| | Total Dose | Prompt Transient | Proton Fluence | Neutron Fluence |
|---|---|---|---|---|
| LED | M | M | L | L |
| Laser Diodes | M | M | L | L |
| Couplers / Connectors | L | L | L | L |
| IO Device / Modulator | L | L | L | L |
| Optical Fiber | H | H | L | L |
| Photodiode / Detector | M | M | L | L |

**Priority Level for Future Testing**

- Low
- Medium
- High

**Status of Prior Studies**

L - Incomplete

M - Adequate

H - Good

Thus, many more materials and devices may be appropriate for the natural space environment than for the other nuclear related environments.

Our review suggests that there may be polymer EO structures that will actually improve with exposure to ionizing radiation. We have seen that radiation can increase the refractive index of a polymer, and that greater stability of the poled state can be achieved by radiation exposure following poling. Such possibilities should clearly be borne in mind when materials and fabrication techniques are selected for radiation study.

A particularly attractive area for the application of polymer-based modulators is the modulation of microwave signals. As we have noted, polymers are well-suited for these applications because the optical and microwave refractive indices are essentially equal. As a result, successful modulation at several tens of GHz has been achieved. Polymer-based microwave traveling wave modulators and related test structures should be subjected to radiation with the intent of measuring the effects of radiation on the devices and also on the optical and microwave refractive indices. If these two indices are affected by different rates by radiation, either high dose rate or total dose, then there may be an observed reduction in the maximum frequency at which modulation can be achieved.

In spite of the fact that polymer technology is not fully matured, it holds very exciting prospects for applications in high reliability, hardened systems. The polymer-based modulator technology has many advantages, and while susceptible to various types of radiation effects, generally large radiation doses are required to cause significant changes. Certainly, most of these radiation effects will occur at doses above typical natural space environment mission requirements. In addition, we have seen that radiation is often used as a tool to improve the performance and quality of these materials and devices. It should be emphasized also that the radiation effects community must pay particular attention to the reliability aspects of this technology so that hardness assurance and high reliability can be simultaneously achieved.

The very rapid recent progress and intense level of effort on the development of EO devices in polymers and semiconductors suggests that these material classes may surpass $LiNbO_3$ and $LiTaO_3$, even though the latter materials enjoy a greater commercial availability at the present time. As we have already pointed out, there are inherent advantages in using polymers and semiconductors compared with $LiNbO_3$ and $LiTaO_3$ devices. Thus, the polymer and semiconductor EO technologies may "leapfrog" those of $LiNbO_3$ and $LiTaO_3$. In addition, if $LiNbO_3$ and $LiTaO_3$ are rapidly surpassed by polymers and/or semiconductors in quality and capability, then their commercial availability may actually be significantly less in the future. Prior to funding significant efforts on radiation effects and radiation hardness assurance in $LiNbO_3$ and $LiTaO_3$ EO devices, and effort should be made to determine as precisely as possible what the projected future of these devices is and what role they will play in military and space systems. It is also important to note

that the availability of these devices for military applications will be influenced by the general commercial availability, which will be driven in turn by general commercial viability of $LiNbO_3$ and $LiTaO_3$ devices. Such an availability assessment is outside the scope of the current effort. There is enough uncertainty in future directions to warrant undertaking such an assessment before committing significant resources to hardening efforts on $LiNbO_3$ and $LiTaO_3$ EO devices.

With regard to radiation effects, two general attributes we can ascribe to SLMs are that first, these are complex devices, making difficult to sort out radiation effects mechanisms, and second, very little work has been done as yet on radiation effects in SLMs. The complexity and variety of SLMs suggests that radiation effects studies will have to be done on a case by case basis, and that it will be extremely difficult to derive general characteristics about radiation response that will be widely applicable to many SLM types. Many of components that make up SLMs are similar to the modulator structures we have already discussed. These materials and devices, and also liquid crystals, should be relatively hard to total dose ionizing radiation effects since they are relatively imperfect materials. The class of SLMs that are based on Si substrates, and contain Si devices of one sort or another are an exception. If in the process of integrating various types of device structures on a Si substrate, $SiO_2$ oxide isolation techniques are used, then one should take care to detect oxide-related total dose effects which are well know to occur at relative low doses in commercial Si integrated circuits.

SLMs containing GaAs components many be affected by neutron and/or proton-induced displacement damage effects. This would also be true of SLMs that contain standard Photonic elements such as microdot lasers or photodiodes. Those SLMs that depend on Si photodiodes for their operation will be sensitive to pulse ionizing radiation and should be checked for these effects.

In the case of the acousto-optic devices, test structures should be designed that allow one to determine the effect of irradiation on the elastic and acoustic properties of the material without the interfering effects of radiation-induced changes in optical properties. Certainly, one would expect the elastic properties of materials to be temporarily altered by intense transient pulses of ionizing radiation. Care must be taken to insure that the observed effects are not due to changes in some other external parameter such as temperature.

A more attractive and fundamental solution to the sensitivity of photodetectors and modulators to transient ionizing radiation is to avoid first window (800 - 900 nm) photonics that employ Si substrates. Because Si is an indirect bandgap material, wide *I* regions are required to achieve satisfactory responsivity to light signals. GaAs and InGaAsP are direct bandgap materials and achieve sufficient responsivity to light signals with much thinner active regions. The thin active region reduces sensitivity to ionizing radiation. Thus, for radiation environments second (1300 nm) and third (1550 nm) window photonic components that use III-V materials are more appropriate. An added benefit is that most of the passive fiber components

such as fibers and couplers are less sensitive to total dose at these longer wavelengths.

Displacement damage causes a reduction in minority carrier lifetime which degrades the performance of laser diode and LED devices at relatively low neutron and proton fluences. Therefore, modulator structures that contain phototransitors or other bipolar devices should be avoided. Improved design efforts should be undertaken to select materials that are less sensitive to ionizing radiation.

## 4.2 RECOMMENDATIONS.

We recommend that extensive radiation characterization of polymer materials and devices be undertaken for three principal reasons. The fact that there are many attractive features of polymer based waveguides and modulators, not the least of which is an excellent compatibility with semiconductor processing technologies. Thus, one can anticipate that polymer-based devices will find broad usage in future photonic systems. In spite of their positive attributes, before these devices can be employed in hardened systems their radiation response characteristics must be thoroughly explored and defined. We have emphasized that many of the properties of polymers in general, and NLO-active polymers in particular, are susceptible to radiation effects. The development of polymer waveguides and modulators is an emerging technology that still remains to be fully investigated. One aspect of this early stage of evolution is that there have been only a very few studies of the effects of radiation on the material and device properties of polymer-based photonic devices. Another is that timely studies of radiation effects can provide guidance for further development of the technology in those directions that will lead to hardened, high reliability materials and devices.

Polymer-based, materials, waveguides and modulators selected for radiation characterization should be restricted to those materials that have the highest reliability. In particular, EO devices that have the most stable poled state are the most desirable. Generally, this implies that materials with high glass transition temperatures, $T_g$, should be selected for study. Of the materials that we have mentioned in this review, polyimides presently come closest to satisfying the requirement.

The lack of any substantive, basic radiation effects studies of polymer-based waveguides and modulators indicates that fairly basic studies must be performed that emphasize the discovery and elucidation of the basic mechanisms of the effects of radiation. The absolute value of the refractive index and the electro-optic coefficient of polymers are critical material parameters whose response to irradiation must be established.

A radiation effects study should be carried out that focuses on the investigation of the response of various poling parameters to radiation. A matrix of parameters should be selected, such as method of dopant incorporation, poling field, atmosphere and temperature, post-poling treatment, and extent of post-poling crosslinking. Then, the effects of radiation on a set of EO-active samples in which these parameters are intentionally varied should be determined.

With regard to a radiation effects and RHA effort in $LiNbO_3$ and $LiTaO_3$ EO materials and devices, we recommend two broad parallel efforts: 1) Studies of the basic mechanisms of radiation effects, including effects of various dopants and waveguide fabrication techniques, and 2) studies of radiation effects on state-of-the-art EO devices. These efforts can be carried out simultaneously, and the results of the basic mechanisms studies should feed into process modifications that will produce EO devices with greater radiation hardness assurance.

Radiation effects tests of SLMs will be complicated to conduct and difficult to interpret. They should be carried out with special attention to closely controlling all external parameters such as temperature and bias. Such studies should be conducted by teams of SLM experts from the SLM vendor and radiation effects experts.

SECTION 5

REFERENCES

1. C. H. Fore III and D. J. Page, " Radiation Effects in Optical Processing Systems, A Quick Look Assessment," (U) DASIAC-91-1428, Defense Nuclear Agency, Alexandria, VA, Nov. 1991. (UNCLASSIFIED)

2. E. W. Taylor, "Dual Use of Photonics in Space Environments," (U) SPIE Proc. Photonics for Space Environments II Conference , Vol. 2215, April, 1993. (UNCLASSIFIED)

3. SPIE Photonics for space Environments Conference, (U) Proc SPIE, Vol 1953, 13 -14 April, 1993. (UNCLASSIFIED)

4. SPIE Photonics For Space Environments II Conference, (U) Proc SPIE, Vol 1953, 13 - 14 April, 1993. (UNCLASSIFIED)

5. SPIE Optical fiber Sensors Conference, (U) Proc. SPIE, Vol. 2360, Glasgow, Scotland, Oct. 1994. (UNCLASSIFIED)

6. SPIE Optical Fiber Sensing and Systems in Nuclear Environments Conference, (U) Proc. SPIE, Vol. 2425, Mol, Belgium, Oct. 1994. (UNCLASSIFIED)

7. IEEE Transaction on Nuclear Science, (U) Vol. 41, No. 6, Conference on Nuclear Space and Radiation Effects (NSREC '94), Tucson, AZ, July 1994. (UNCLASSIFIED)

8. SPIE Fiber Optic Materials and Components, (U) Proc SPIE, Vol. 2290, Optics, Imaging, and Instrumentation Conference, San Diego, CA, July 1994. (UNCLASSIFIED)

9. R. G. Pirich, M.C. Stauber, and J. DeCarlo, "Effect of Weakly and Strongly Ionizing Radiation on the Optical Infrared and Dielectric Properties of Porous Sol-Gel Glasses," (U) Proc. Fiber Optic Materials and Components, Vol., pp. 2290 - 31, July 1994. (UNCLASSIFIED)

10. R. Gutierrez, G. Swift, C. Barnes, A. Johnston, and M. McLandrich, "Radiation effects in all-glass Wavelength Division Multiplexer (WDM) couplers," (U) SPIE Proc. Fiber Optic Materials and Components, Vol., pp. 2290 - 32 , July ,1994. (UNCLASSIFIED)

11. J. Hatch, "Change in FWHM of AlGaAs LEDs subjected to mixed neutron and gamma radiation," (U) SPIE Proc. Fiber Optic Materials and Components, Vol. 2290-33, pp. 278 - 288, July 1994. (UNCLASSIFIED)

12. S. Saggese and R. Greenwell, "Standards development for fiber optic spectroscopic components for adverse environments," (U) SPIE Proc. Fiber Optic Materials and Components, Vol. , pp. 2290 - 34 , July 1994. (UNCLASSIFIED)

13. Hopkinson, G., C. Baddiley, D. Guy, and J. Parsons, "Total dose and proton testing of a commercial HgCdTe array," (U) IEEE Transaction on Nuclear Science, Vol. 41, No. 6, pp. 1966-1973, Conference on Nuclear Space and Radiation Effects (NSREC '94), July 1994 . (UNCLASSIFIED)

14. C. Dale, L. Chen, P. McNulty, P. Marshall, and E. Burke, "A Comparison of Monte Carlo and Analytic Treatments of Displacement Damage in Si Microvolumes," (U) IEEE Transaction on Nuclear Science, Vol. 41, No. 6, pp. 1974-1983, Conference on Nuclear Space and Radiation Effects (NSREC '94), Tucson, AZ, July 1994 . (UNCLASSIFIED)

15. B. Rogina, "Radiation Testing of PCS Optical Fiber for Dose Level Sensor Application," (U) *SPIE Proc. Optical fiber Sensors Conference,* Vol. 2360, pp. 468-470, Glasgow, Scotland, Oct. 1994. (UNCLASSIFIED)

16. P. Ferdinand, et al, "Optical Fiber Bragg Grating Sensors for Structure Monitoring within Nuclear Power Plants," (U) SPIE Proc. Optical Fiber Sensing and Systems in Nuclear Environments Conference, Vol. 2425, pp. 11-20, Mol, Belgium, Oct. 1994. (UNCLASSIFIED)

17. E . Dianov, et al, "Radiation Resistance of Optical Fibers with Fluorine Doped Silica Cladding," (U) SPIE Proc. Optical Fiber Sensing and Systems in Nuclear Environments Conference, Vol. 2425, pp. 58-62, Mol, Belgium, Oct. 1994. (UNCLASSIFIED)

18. V. Matejec, et al, "Attenuation of Silica Optical Fibers in Nuclear Environment and its Dependence on the Properties of Materials for Fiber Preparation," (U) SPIE Proc. Optical Fiber Sensing and Systems in Nuclear Environments Conference, Vol. 2425, pp. 63-73, Mol, Belgium, Oct. 1994. (UNCLASSIFIED)

19. H. Lischka, et al, "Radiation Effects in Optoelectronic Devices," (U) SPIE Proc. Optical Fiber Sensing and Systems in Nuclear Environments Conference, Vol. 2425, pp. 43-52, Mol, Belgium, Oct. 1994. (UNCLASSIFIED)

20. H. Henschel, O. Kohn, and H. Schmidt, " Radiation Sensitivity of Passive Components of Fiber Optic Data Transfer and Sensor Systems," (U) SPIE

Proc. Optical Fiber Sensing and Systems in Nuclear Environments Conference, Vol. 2425, pp. 155-163, Mol, Belgium, Oct. 1994. (UNCLASSIFIED)

21. K. Obara, et al, "Development of optical components for in-vessel viewing systems used for fusion experimental reactor," (U) SPIE Proc. Optical Fiber Sensing and Systems in Nuclear Environments Conference, Vol. 2425, pp. 115-122, Mol, Belgium, Oct. 1994. (UNCLASSIFIED)

22. Barnes, C., "Radiation Effects in 1.06 µm InGaAs LEDs and Si Photodiodes," (U) IEEE Trans Nuc. Sci, Vol. 27, No. 6, July 1984. (UNCLASSIFIED)

23. Barnes, C., "Radiation Effects on Light Sources and Detectors," (U) SPIE Adverse Environments Conference, Vol. 541, pp. 138-144, Albuquerque, NM, May 1985. (UNCLASSIFIED)

24. Iida, H., H. Sumita and J. Logan, "Fusion Neutron Testing for Fibers and Devices," (U) Journal of Nuclear Science and Technology, pp. 964-966, Nov. 1983. (UNCLASSIFIED)

25. Dimiduk, K., C. Ness and J. Foley, "Electron Irradiation of InGaAsP LEDs and InGaAs Photodetectors," (U) IEEE Trans. Nuc. Sci., Vol. NS-32, No. 6, p. 1748, December, 1985. (UNCLASSIFIED)

26. Lischka, H., H. Henschel, W. Lennartz and H. Schmidt, "Radiation Sensitivity of Light Emitting Diodes (LED), Laser Diodes (LD) and Photodiodes (PD)," (U) RADECS '91, pp. 404-408, La Grande-Motte, France, Sept. 1991. (UNCLASSIFIED)

27. Lischka, H., H. Henschel, W. Lennartz, O. Kohn and H. Schmidt, "Radiation Sensitivity of Light Emitting Diodes, Laser Diodes, Photodiodes and Optocouplers," (U) RADECS '93, pp. 226-231, Saint-Malo, France, Sept. 1993. (UNCLASSIFIED)

28. Sharma, A., G. Jacobs and J. Plante, "NASA/GSFC Opto-Electronic Components Applications and Evaluations," (U) DOD Fiber Optics '92, pp.359-362, McClean, VA, March 1992. (UNCLASSIFIED)

29. LaBel, K., "A Spacecraft Fiber Optic Data System - Radiation Effects," (U) RADECS '91, pp. 412-415, La Grande-Motte, France, Sept. 1991. (UNCLASSIFIED)

30. Carson, R. and J. Chow, "Neutron Effects in High Power GaAs Laser Diodes," (U) IEEE Trans. Nuc. Sci., Vol. NS-36, No. 6, p. 2076, Dec. 1989. (UNCLASSIFIED)

31. Marshall, P., C. Dale and M. Long, "Space Radiation Effects on Optoelectronic Components for a Fiber Optic Data Bus," (U) DOD Fiber Optics '92, pp. 359-362, McClean, VA, March 1992. (UNCLASSIFIED)

32. Kalma, A. and W. Hardwick, "Radiation Effects on Optoelectronics," (U) IEEE Trans. Nuc. Sci., Vol. NS-25, No. 6, p. 1483, Dec. 1978. (UNCLASSIFIED)

33. Henschel, H., O. Kohn and H. Schmidt, "Radiation Sensitivity of Passive Components of Fiber Optic Data Transfer and Sensor Systems," (U) SPIE Proc. Optical Fiber Sensing and Systems in Nuclear Environments Conference, Vol. 2425, pp. 155-162, Mol, Belgium, Oct. 1994. (UNCLASSIFIED)

34. Henschel, H., O. Kohn, H. Schmidt and D. Rittich, "Contribution of Butt-Joint Connectors and Lens Connectors to the Radiation Induced Loss of Optical Fiber Cables at 1300 nm Wavelength," (U) RADECS '91, pp. 401-403, La Grande-Motte, France, Sept. 1991. (UNCLASSIFIED)

35. Friebele, E. J., K. Long, C. Askins and M. Gingerich, "Radiation Response of Optical Fibers and Selfoc Microlenses at 1.3 µm," (U) SPIE, Vol. 506, pp. 202-208, San Diego, CA, July 1984. (UNCLASSIFIED)

36. Ellis, R. and W. Johnson, "PCS Cable Connector Terminations, Radiation Exposure and Testing," (U) SPIE, Vol. 506, pp. 139-148, San Diego, CA, July 1984. (UNCLASSIFIED)

37. Zucker, J. R. Clarke and R. Narciso, "Transient Attenuation in Connectors to PCS Fibers and in Glass-on-Glass Fibers Induced by Pulsed X-Rays," (U) SPIE, Vol. 506, pp. 165-168, San Diego, CA, July 1984. (UNCLASSIFIED)

38. Jabr, S., "Economics and Technology of Integrated Optical Modulators: 1969-1999," (U) SPIE Proc., CR-45, P.180, Boston, MA, Sept. 1993. (UNCLASSIFIED)

39. Findakly, T., C. Teng and L. Walpita, "Wideband NLO Organic External Modulators," (U) SPIE Proc., Vol. 1476, pp. 14. , ORLANDO, FL, APR. 1991. (UNCLASSIFIED)

40. Chen, R. T., "Polymer Based Photonic Integrated Circuits," (U) Optics and Laser Tech., Vol. 25, pp. 347, 1993. (UNCLASSIFIED)

41. Chen, R. T., "Polymer-based Passive and Active Guided Wave Devices and Their Applications," (U) SPIE Proc., Vol CR-45, pp. 198, Boston, MA, Sept. 1993. (UNCLASSIFIED)

42. Feger, C., "Evaluating Polyimides as Lightguide Materials," (U) Applied Optics, Vol. 27, pp. 21, 1988. (UNCLASSIFIED)

43. Salley, J., T. Miwa, and C. Frank, "Intramolecular Charge Transfer in Aromatic Polyimides," (U) Material Research Society Proc., Vol. 227, pp. 117, Anaheim, CA, Feb. 1991. (UNCLASSIFIED)

44. Beuhler, A., D. Wargowski, T. Kowalczyk, and K. Singer, "Optical Polyimides for Single Mode Waveguides," (U) SPIE Proc., Vol. 1849, pp. 92, Los Angeles, CA, Jan. 1993. (UNCLASSIFIED)

45. Holland, W., M. Kuzyk, K. Singer, and J. Sohn, "Non-Linear Optical Polymer Films," (U) 14th European Conference on Optical Communications, pp. 300, Copenhagen, Denmark, Sept. 1988. (UNCLASSIFIED)

46. Ermer, S., J. Valley, R. Lytel, G. Lipscomb, T. Van Eck, and D. Girton, "DCM Polyimide System for Triple Track Poled Polymer Electro-optic Devices," (U) Applied Physics Letters, Vol. 61, pp. 2272, 1992. (UNCLASSIFIED)

47. Chakravorty, K., "Ultraviolet Defined Selective In-diffusion of Organic Dyes in Polyimide for Applications in Optical Interconnect Technology," (U) Applied Physics Letters, Vol. 61, pp. 1163, !992. (UNCLASSIFIED)

48. Sullivan, C., "Optical Waveguide Circuits for Printed Wireboard Interconnections," (U) SPIE Proc. , Vol. 994, pp. 92, Boston, MA, Sept. 1988. (UNCLASSIFIED)

49. Hewak, D., F. Picard, and H. Jin, "Optical Waveguides in Polyimide by Direct Laser Writing Utilizing Thermal Curing," (U) First Int. Workshop on Photonic Networks, Components, and Applications Proc., pp. 265, 1991. (UNCLASSIFIED)

50. Beeson, K., M. McFarland, W. Pender, J. Shan, C. Wu, and J. Yardly, "Laser Written Polymeric Optical Waveguides for Integrated Optical Device Applications," (U) SPIE Proc., Vol. 1794, pp. 397, Boston, MA, Sept. 1992. (UNCLASSIFIED)

51. Paul, D., B. Markey, R. Hefele, and B. Pontano, "Organic Polymer Integrated Optical Waveguide Devices," (U) SPIE Proc. Vol. 1849, pp. 342, Los Angeles, CA, Jan. 1993. (UNCLASSIFIED)

52. Eremeeva, E., M. Votinov, and A. Dokukina, "Effect of Low Molecular Weight Additive on Radiation Strength of Transparent Polymers," (U) Sov. Jour. Optical Tech., Vol. 53, pp. 361, 1986. (UNCLASSIFIED)

53. Demkovich, P., M. Kotlyar, V. Kulagin, and K. Sonin, "Modification of Optical Properties and Dynamics of Laser Ultraviolet Ablation of Polyimide," (U) Sov. Jour. Quantum Elec. Vol. 22, pp. 400, 1990. (UNCLASSIFIED)

54. Aleshin, A., and A.. Suvorov, "Inversion of the Type of Conduction in Ion Irradiated Polyimide Films," (U) Sov. Physics - Solid State, Vol. 35, pp. 364, 1993. (UNCLASSIFIED)

55. Rye, R., "Spectroscopic Evidence for Radiation Induced Crosslinking of Poly(tetrafluoroethylene)," (U) Jour. Polymer Sci., Vol. 31, pp. 357, 1993. (UNCLASSIFIED)

56. Jones, R., G. Salmon, and I. Ward, "Radiation Induced Crosslinking of Polyethelene in the Presence of Acetylene: A Gel Fraction, UV-Visible, and ESR Spectroscopy Study," (U) Jour. Polymer Sci., Vol. 31, pp. 807, 1993. (UNCLASSIFIED)

57. Zhao, Y., D. Poirier, and J. Weaver, "Electron Stimulated Polymerization of Solid $C_{60}$," (U) Applied Physics Letters, Vol. 64, pp. 577, 1994. (UNCLASSIFIED)

58. Qi, Y., L. Limin, and L. Changjiang, "Radiation Induced Variations of Electrical Conductivity in Polyaniline," (U) Chinese Physics Letters, Vol. 11, pp. 113, 1994. (UNCLASSIFIED)

59. Kassem, M., N. Madi, N. Rehim, and W. Taleb, "Radiation and Field Induced Effects on The Electrical and Optical Properties of Polyvinylidene Chloride," (U) Materials Letters, Vol. 19, pp. 87, 1994. (UNCLASSIFIED)

60. Rabie, S., S. Moharram, A. Daghistani, and M. Moharram, "Effect of Gamma Irradiation on Electrical Conductivity of Metal Chloride Treated Polyacrylamide," (U) Polymer Plastics Tech. and Eng., Vol. 32, pp. 397, 1993. (UNCLASSIFIED)

61. Soliman, F., and H. Ashry, "Radiation Effects on Non-Linear Resistances," (U) Jour. of Material Sci.: Materials in Electronics, Vol. 4, pp. 293, 1993. (UNCLASSIFIED)

62. Kanofsky, A. and W. Herman, "Radiation effects of Polymer Waveguides," (U) SPIE Proc. Vol. 1794, pp. 234, Boston, MA, Sept. 1992. (UNCLASSIFIED)

63. McCaughan, "Critical Materials Issues in the Performance and Manufacturability of $LiNbO_3$ Integrated optics," (U) SPIE Critical Reviews of Optical Science and Technology, CR-45, pp. 15, Boston, MA, Sept. 1993. (UNCLASSIFIED)

64. Taylor, E., "Radiation Effects in Guided Wave Devices," (U) SPIE Proc., Vol. 1794, Integrated Optic Circuits II, pp. 54-61, Boston, MA, Sept. 1992. (UNCLASSIFIED)

65. Taylor, E., A. Sanchez, M. Kelly, S. Chapman, J. Stohs, E. Kinsley and D. Craig, "Radiation Induced Crosstalk in a Proton Exchanged $LiNbO_3$ Directional Coupler" (U) SPIE Proc Photonics for Space Environments III, Vol. 2482, Orlando, FL, April 1995. (UNCLASSIFIED)

66. Taylor, E., R. Padden, A. Sanchez, S. Chapman, J. Berry and S. De Walt, "Radiation Induced Crosstalk in Guided Wave Devices," (U) Proc. SPIE, Vol. 1474, Orlando, FL, April 1991. (UNCLASSIFIED)

67. Padden, R., E. Taylor, A. Sanchez, S. Chapman, J. Berry, S. De Walt and K. Wong, "LiTaO3 and LiNbO3 : Ti Responses to Ionizing Radiation," (U) Proc. SPIE, Vol. 1474, Orlando, FL, April 1991. (UNCLASSIFIED)

68. Taylor, E., "Ionization Induced Refractive Index and Polarization Effects in $LiNbO_3$: Ti Directional Coupler Waveguides," (U) IEEE/OSA Journal of Lightwave Technology, Vol. 9, No. 3, pp. 335 - 340, March, 1991. (UNCLASSIFIED)

69. Taylor, E., "Radiation Effects in Guided Wave Devices," (U) SPIE Proc. , Vol. 1794, Integrated Optic Circuits II, pp. 54-61, Boston, MA, Sept. 1992. (UNCLASSIFIED)

70. Antonov, V., P. Arsenev, B. Baranov, N. Barinova, E. Kustov, and I. Linde, "Radiation defects research in Single Crystals of Lithium Niobate," (U) Radiation Physics and Chem., Vol. 10, pp. 241, 1977. (UNCLASSIFIED)

71. Schmidt, R., R. Cross, and A. Glass, "Optically Induced Crosstalk in Lithium Niobate Waveguide Switches," (U) Journal of Applied Physics, Vol. 51, pp. 90, 1980. (UNCLASSIFIED)

72. Abgaryan, G., A. Matviichuk, and G. Kholodar, "Radiation Stimulated Rotation of the Axis of Unipolar Properties in Lithium Niobate Crystals," (U) Soviet Physics - Tech. Physics, Vol. 30, pp. 1423, 1985. (UNCLASSIFIED)

73. Evans, B., "Radiation Induced Attenuation in Integrated Optic Materials," (U) SPIE Proc., Vol. 1177, pp. 280, Boston, MA, Sept. 1989. (UNCLASSIFIED)

74. Brannon, P., "Transient Radiation Induced Absorption at 1061 nm in Lithium Niobate and MgO:$LiNbO_3$," (U) IEEE Trans. Nuclear Sci., Vol. 41, pp. 642, Dec. 1994. (UNCLASSIFIED)

75. Roeske, F., D. Jander, G. Lancaster, M. Lowry, and W. Tindall, "Preliminary Radiation Hardness Testing of Lithium Niobate: Titanium Optical Directional coupler Modulators Operating at 810 nm," (U) SPIE Proc., Vol. 787, pp. 36, Orlando, FL, May 1987. (UNCLASSIFIED)

76. Taylor, E., "Behavior of Coupled Waveguide Devices in Adverse Environments," (U) SPIE Proc. 1314, 155 (1990). (UNCLASSIFIED)

77. Taylor, E., V. Wilson, A. Sanchez, S. DeWalt, S. Chapman, M. Vigil and R. Padden, "Nuclear-induced Refractive Index Effects Observed in Typical Guided Wave Devices," (U) SPIE Proc. 1177, 278 (1989). (UNCLASSIFIED)

78. Kanofsky, A. and W. Minford, "Radiation Effects on Proton Exchange Waveguides," (U) SPIE Proc. 1794, 62 (1992). (UNCLASSIFIED)

79. Henschel, H., O. Kohn and H. Schmidt, "Radiation-Induced Transmission Loss of Integrated Optic Waveguide Devices," (U) SPIE Proc. 1974, 79 (1992). (UNCLASSIFIED)

80. Smith, D., K. Hugenberg, J. Flatley and H. Garrett, "Transient Radiation Effects in Annealed Proton Exchange $LiNbO_3$ and $LiTaO_3$ Waveguides," (U) SPIE Proc. 1794, 70 (1993). (UNCLASSIFIED)

81. West, R. and S. Dowling, "Radiation Effects on a Lithium Tantalate Optical Waveguide Structure," (U) Elect. Lett. 29, 970 (1993). (UNCLASSIFIED)

82. Taylor, E., R. Padden, A. Sanchez, S. Chapman, J. Berry and S. DeWalt, "Radiation-Induced Crosstalk in Guided Wave Devices," (U) SPIE Proc. 1474, 126 (1991). (UNCLASSIFIED)

83. Taylor, W., "Radiation Effects Observed in Selected Guided Wave Devices," (U) p. 229 in Critical Reviews of Optical Science and Technology, SPIE Proc. CR-45, K. Wong and M. Razeghi, Editors (1993). (UNCLASSIFIED)

84. Taylor, E. "Ionization-induced Refractive Index and Polarization Effects in $LiNbO_3$:Ti Direction Coupler Waveguides," (U) IEEE Jour. Lightwave Tech. 9, 335 (1991). (UNCLASSIFIED)

85. Brannon, P. , "Transient Radiation-Induced Absorption at 1061 nm in $LiNbO_3$ and MgO:$LiNbO_3$,"(U) IEEE Trans., Nuc. Sci. 41, 642 (1994). (UNCLASSIFIED)

86. Taylor, E., A. Sanchez and S. DeWalt, "Radiation Effects in Photonic Technology Devices," (U) p. 29 in Conf. Proc., Second Biennial Dept. Of Defense Fiber Optics and Photonics Conf. McLean, VA (1992). (UNCLASSIFIED)

87. Taylor, E., "On the Measurement of Radiation Induced Crosstalk in Polarization Preserving Optical Fibers and Directional Coupler Waveguides," (U) p. 391 In Conf. Proc.: First European Conf. On Radiations and Their Effects on Devices and Systems (RADECS 91) (1992). (UNCLASSIFIED)

88. Taylor, E., "Radiation Effects in Guided Wave Devices," (U) SPIE Proc. 1794, 54 (1992). (UNCLASSIFIED)

89. Schmidt, R., R. Cross and A. Glass, "Optically Induced Cross-talk in $LiNbO_3$ Waveguide Switches," (U) Jour. Appl. Phys. 51, 90 (1980). (UNCLASSIFIED)

90. Becker, R., and R. Williamson, "Photorefractive Effects in $LiNbO_3$ Channel Waveguides: Model and Experimental Verification," (U) Appl Phys. Lett. 47, 1024 (1985). (UNCLASSIFIED)

91. Arsenault, H., and Y. Sheng, "An Introduction to Optics in Computers," (U) SPIE, Vol TT8, Bellingham, WA (1992). (UNCLASSIFIED)

92. Esener, S., "Silicon Based Smart Spatial Light Modulators: Technology and Applications to Parallel Computers in Digital Optical Computing," (U) R. Athale, Edit, SPIE Critical Reviews of Optical Science and Technology CR-35, 100 (1990). (UNCLASSIFIED)

93. Ross, W. and D. Lambeth, "Advanced Magnetic-Optical Spatial Light Modulator Device Development," (U) SPIE Proc. 1562, 93 (1991). (UNCLASSIFIED)

94. Suzuki, Y., "Spatial Light Modulators and Applications," (U) SPIE Proc. 2321, 665 (1993). (UNCLASSIFIED)

95. Berg, N. and J. Speulstra, "The Operation of Acoustic Surface Wave Delay Lines in a Nuclear Environment," (U) Trans. Nucl. Sci. NS-20, 137 (1973). (UNCLASSIFIED)

96. Berg, N. and J. Udelson, "Nuclear Radiation Effects on Surface Wave Devices," (U) Trans. Nucl. Sci. NS-21, 141 (1974). (UNCLASSIFIED)

97. Berg, N. and J. Udelson, "The Effects of Pulsed Ionizing Radiation on the Operation of Surface Acoustic Wave Amplifiers and Convolvers," (U) Trans. Nucl. Sci. NS-22, 2503 (1974). (UNCLASSIFIED)

98. Hines, J., C. Dale and W. Stapor, "Ionizing Space Radiation Effects on Surface Acoustic Wave Resonators," (U) SPIE Proc. 1784, 206 (1992). (UNCLASSIFIED)

99. Taylor, E., A. Sanchez, S. DeWalt, "Radiation Effects in a Photonic Technology Device," (U) p. 29 in Conf. Proc., DoD Fiber Optics '92, McLean, VA (1992). (UNCLASSIFIED)

100. Taylor, E., "Radiation Effects Observed in Selected Guided Wave Devices," (U) p. 299 in Integrated Optics and Optoelectronics, SPIE Press, Bellingham, WA (1993). (UNCLASSIFIED)

101. Taylor, E., A. Sanchez, S. DeWalt, R. Padden, S. Chapman, T. Monarski, D. Craig and D. Page, "Radiation-Induced Effects in Acousto-Optic Devices," (U) SPIE Proc. 1974, 217 (1992). (UNCLASSIFIED)

102. Taylor, E., A. Sanchez, S. DeWalt, D. Craig, M. Kelly, S. Chapman and M. Mitcham, "Radiation Effects Observed in a Spatial Light Modulator," (U) p. 17 in Conf. Proc., DoD Fiber Optics '94, McLean, VA (1994). (UNCLASSIFIED)

103. De La Rue, R. and J. Marsh, "Integrated Technologies for III-V Semiconductor Optoelectronics Based on Quantum Well Waveguides," (U) p. 259 in Integrated Optics and Optoelectronics, SPIE Critical Reviews of Optical Science and Technology CR-45, K. Wong and M. Razeghi, Editors (1993). (UNCLASSIFIED)

104. Shaw, N. and A. Carter, "Optoelectronic Integrated Circuits for Microwave Optical Systems," (U) p. 90 in Microwave Journal, October, 1993. (UNCLASSIFIED)

105. Shimomura, K and S. Arai, "Semiconductor Waveguide Optical Switches and Modulators," (U) Fiber and Integrated Optics 13, 65 (1992). (UNCLASSIFIED)

106. Drabik, T., "Devices for Optoelectronic Integrated Systems," (U) SPIE Proc. 1562, 194 (1991). (UNCLASSIFIED)

107. Ebeling, K., Integrated Optoeletronics, (U) Springer-Verlag, New York, NY (1993). (UNCLASSIFIED)

108. Leonberger, F. and J. Donnelly, "Semiconductor Integrated Optic Devices," (U) p. 317 in guided Wave Optoelectronics, T. Tamir, Editor, Springer-Verlag (1988). (UNCLASSIFIED)

109. Weatherford, T., L. Tran, W. Stapor, E. Petersen, J. Langworthy, D. McMorrow, W. Abdel-Kader and P. McNulty, "Proton and Heavy Ion Upsets in GaAs MESFET Devices," (U) IEEE Trans. Nucl. Sci. 38, 1450 (1991). (UNCLASSIFIED)

110. McMorrow, D., T. Weatherford, A. Knudson, L. Tran, J. Melinger and A. Campbell, "Single Event Dynamics of High Performance HBTs and GaAs MESFETs," (U) IEEE Trans. Nuc. Sci. 40, 1858 (1993). (UNCLASSIFIED)

111. Weatherford, T., D. McMorrow, W. Curtice, A. Knudson and A. Campbell, "Single Event Induced Charge Transport Modeling of GaAs MESFETs," (U) IEEE Trans. Nucl. Sci. 40, 1867 (1993). (UNCLASSIFIED)

112. Islam, N., J. Howard, O. Fageeha and R. Block, "A Model for the Bipolar-like Response of GaAs MESFETs to a High Dose Rate Environment," (U) IEEE Trans. Nucl, Sci. 41, 2494 (1994). (UNCLASSIFIED)

113. Anderson, W., J. Gerdes and J. Roussos, "Temperature Dependent GaAs MMIC Radiation Effects," (U) IEEE Trans. Nuc. Sci. 40, 1735 (1993). (UNCLASSIFIED)

114. Dupont-Nivet, E. and M. Pasquali, "Neutron Effects on HEMT Devices," (U) p. 189 in First European Conf. On Radiation and Its Effects on Components and Systems (RADECS 91) (1992). (UNCLASSIFIED)

115. Hughlock, B., A. Johnston, T. Williams and J. Arrang, "A Comparison of Charge Collection Effects Between GaAs MESFETs and III-V HFETs," (U) IEEE Trans. Nuc. Sci. 39, 1642 (1992). (UNCLASSIFIED)

116. Saito, S., "Reliability of Low Noise HEMTs Under Gamma Ray Irradiation," (U) IEICE Trans. Elect. E76-C, 1379 (1993). (UNCLASSIFIED)

117. Kearney, M., N. Couch, M. Edwards and I. Dale, "Neutron Radiation Effects in GaAs Planar Doped Barrier Diodes Barrier Diodes," (U) IEEE Trans. Nuc. Sci. 40, 102 (1993). (UNCLASSIFIED)

118. Walters, R., S. Messenger, G. Summers, E. Burke and C. Keavney, "Space Radiation Effects in InP Solar Cells," (U) IEEE Trans. Nuc. Sci. 38, 1153 (1991). (UNCLASSIFIED)

119. Auret, F., S. Goodman, G. Myburg and W. Meyer, "Electrical Characterization of Defects Introduced in N-GaAs by Alpha and Beta Irradiation from Radionuclides," (U) Appl. Phys. A A56, 547 (1993). (UNCLASSIFIED)

120. Wendler, E., Wesch and G. Gotz, "Radiation Damage and Optical Properties of $Ar^+$ Implanted GaP," (U) Jour. Appl. Phys. 70, 144 (1991). (UNCLASSIFIED)

121. Carlone, C., M. Parenteau, C. Actik, S. Khanna, N. Rowell and J. Gerdes Jr., "Radiation Effects on Heavily Doped n-GaAs," (U) p. 183 in first European Conf. On Radiation and Its Effects on Components and Systems (RADECS 91) (1992). (UNCLASSIFIED)

122. Evans, B., H. Hager and B. Hughlock, "5.5 MeV Proton Irradiation of a Strained Quantum Well Laser Diode and a Multiple Quantum Well Broad Band LED," (U) IEEE Trans. Nuc. Sci. 40, 1645 (1993). (UNCLASSIFIED)

123. Hava, S. and N. Kopeika, "Space as an Adverse Environment: Vacuum Surface Gamma Ray Irradiation Effects on LEDs and Photodiodes," (U) SPIE Proc. 721. 2 (1987). (UNCLASSIFIED)

124. Lischka, H., H. Henschel, W. Lennartz and H. Schmidt, "Radiation Sensitivity of Light Emitting Diodes (LEDs) Laser Diodes (LDs) and Photodiodes (PDs)," (U) p. 404 in First European Conf. On Radiation and Its Effects on Components and Systems (RADECS 91) (1992). (UNCLASSIFIED)

125. Lischka, H., H. Henschel, O. Kohn, W. Lennartz and H. Schmidt, "Radiation Effects in Light Emitting Diodes, Laser Diodes, Photodiodes and Optocouplers," (U) p. 226 in Second European Conf. On Radiation and Its Effects on Components and Systems (RADECS 93) (1994). (UNCLASSIFIED)

126. Barnes, C., T. Zipperian and L. Dawson, "Neutron-Induced Trapping Levels in Aluminum Gallium Arsenide," (U) Jour. Elec. Mat. 14, 95 (1985). (UNCLASSIFIED)

127. Friebele, W., P. Marshall, G. Summers, Y. Chen, A. Campbell and J. Langworthy, "Fiber Optic Data Bus Radiation Effects Study," (U) Naval Research Laboratory Report No. NRL/MR/4613-92-6982, Sept. 1992. (UNCLASSIFIED)

128. Marshall, P., and C. Dale, "Space Radiation Effects on Optoelectronic Materials and Components for a 1300 nm Fiber Optic Data Bus," (U) IEEE Trans. Nuc. Sci. 39, 1982 (1992). (UNCLASSIFIED)

129. Marshall, P., C. Dale, E. Friebele and K. LaBel, "Survivable Fiber Based Data Links for Satellite Radiation Environments," (U) p. in SPIE Critical Review Series CR-50 (1993). (UNCLASSIFIED)

130. Barnes, C., "The Effects of Neutron Irradiation on the High Temperature Operation of Injection Laser Diodes," (U) SPIE Proc. 506, 218 (1984). (UNCLASSIFIED)

131. Barnes, C. and J. Wiczer, "Radiation Effects in Optoelectronic Devices," (U) Sandia National Laboratories Report No. SAND84-0771 (1984). (UNCLASSIFIED)

132. Carson, R. and W. Chow, "Neutron Effects in High Power GaAs Laser Diodes," (U) IEEE Trans. Nuc. Sci. 36, 2076 (1989). (UNCLASSIFIED)

133. Barnes, C., "Radiation Hardened Optoelectronic Components: Sources," (U) SPIE Proc. 616, 248 (1986). (UNCLASSIFIED)

134. Friebele, E. J., E. W. Taylor, G. Turquet de Beauregard, J. Wall and C. E. Barnes, "Interlaboratory Comparison of Radiation Induced Attenuation in Optical Fibers, Part I: Steady State Exposures," (U) IEEE/OSA, Journ of Lightwave Technology, Vol 6, No. 2, pp. 165 - 171, Feb. 1988. (UNCLASSIFIED)

135. Taylor, E. W., E. J. Friebele, H. Henschel, C. E. Barnes and J. Krinsky, "Interlaboratory Comparison of Radiation Induced Attenuation in Optical Fibers, Part II: Steady State Exposures," (U) IEEE/OSA Journal of Lightwave Technology, Vol. 8, No. 6, pp. 967 - 976, June, 1990. (UNCLASSIFIED)

136. Taylor, E. W., A. D. Sanchez, S. P. Chapman, S. A. DeWalt, D. M. Craig, M. A. Kelly and M. F. Mitcham, "Responses of a Spatial Light Modulators to Pulsed Electron Irradiations," (U) Proc. Optical Society of America, Spatial Light Modulators and Applications Topical Meeting, 12 - 17 March, 1995. (UNCLASSIFIED)

137. "Procedure for Measuring Radiation Induced Attenuation in Optical Fibers and Optical Cables," (U) NATO Technical Report, AC/243 (Panel IV), TR/2, 28 June 1993. (UNCLASSIFIED)

138. Barnes, C., "Radiation Effects on Light Sources and Detectors," (U) SPIE Proc. 541, 138 (1985). (UNCLASSIFIED)

139. Hopkins, G. Hopkinson and B. Johlander, "Proton Induced Charge Transfer Degradation in CCDs for Near Room Temperature Applications," (U) IEEE Trans Nuc. Sci., Vol. 41, No. 6, July, 1994. (UNCLASSIFIED)

140. Dale, D., B. Cummings, L. Shamey, P. Marshall and A. Holland, "Displacement Damage Effects in Mixed Particle Environments for Shielded CCDs," (U) IEEE Trans. Nuc. Sci., Vol. 40, No. 6, pp. 1628 - 1637, July, 1993. (UNCLASSIFIED)

APPENDIX A

LIST OF PUBLISHED AND UNPUBLISHED TEST DOCUMENTS


1. Addleman, Crawford, Mech, Troyer, Greenwell; Survey of Fiber-optic Sensor for Remote Sensing in Radiologically and Chemically Harsh Environments; (U) 9/9/92 . (UNCLASSIFIED)

2. Alurralde, Victoria, Caro, Gavillet; Nuclear and Damage Effects in Si Produced by Irradiations with Medium Energy Protons; (U) 7/15/91. (UNCLASSIFIED)

3. Askins, Friebele, Schmidt; Correlation of Single Mode Fiber Radiation Response with Fabrication Parameters; (U) 3/20/90. (UNCLASSIFIED)

4. Askins, Shaw, Friebele; Radiation Response Prediction of Single Mode Optical Fiber Waveguides; (U) 9/25/86. (UNCLASSIFIED)

5. Barnes, Dorsky, Johnston, Bergman, Stassinopoulos; Overview of Fiber Optics in the Natural Space Environment; (U) 9/18/90. (UNCLASSIFIED)

6. Barnes, Fleetwood, Shaw, Winokur; Post Irradiation Effects (PIE) in Integrated Circuits; (U) 9/9/91. (UNCLASSIFIED)

7. Barnes, Heflinger, Reel; Effect of Neutron Irradiation on Laser Diode Properties. (UNCLASSIFIED)

8. Barnes, Johnston, Cross, Edmonds, Eslami, Farmanesh, Gutierrez, Lee, McCarty, Nichols, Padgett, Rax, Reier, Schwartz, Shaw, Swift, Watson; Microelectronics Space Radiation Effects Program: Progress Report; Section 5, Photonics Subtask; (U) 02/94. (UNCLASSIFIED)

9. Barnes, Wiczer; Fiber Optic Data Links Optimized for Radiation Environments; (U) 1985. (UNCLASSIFIED)

10. Barnes; Increased Radiation Hardness of GaAs Laser Diodes at High Current Densities; (U) 3/22/74. (UNCLASSIFIED)

11. Barnes; Laser Diode-Induced Photobleaching at Low Temperatures in Co60 Irradiated Fiber; (U) 12/4/82. (UNCLASSIFIED)

12. Barnes; Neutron Damage Effects in Laser Diodes; (U) 12/4/72. (UNCLASSIFIED)

13. Barnes; Radiation Effects in 1.06 um InGaAs LED's and Si Photodiodes; (U) 3/16/78. (UNCLASSIFIED)

14. Barnes; Radiation Effects on Light Sources and Detectors; (U) 3/7/85. (UNCLASSIFIED)

15. Barnes; Technology Assessment: Radiation Hardened Fiber Optic and Optoelectronic Devices and Systems; (U) 4/15/92. (UNCLASSIFIED)

16. Barnes; The Effects of Neutron Iradiation on the High Temperature Operation of Injection Laser Diodes; (U) 8/22/84. (UNCLASSIFIED)

17. Bates, Hendricks, Shaffer; Neutron Irradiation Effects and Structure of Noncrystalline $SiO_2$; (U) 05/28/74. (UNCLASSIFIED)

18. Beck, Reinhardt and Skutnik; Fiber Optic Trends - Radiation Hardened Fibers: Asking the Right Questions; (U) 5/1/86. (UNCLASSIFIED)

19. Bernhardt, Klein, Fabian, Grzesik, Henschel, Kohn, Schmidt; Excitation Dependent Radiation-Induced Losses in Step-Index Fibers with Undoped Core. (UNCLASSIFIED)

20. Bilodeau, Ewing, Nau, Gingerich, Friebele, Aggarwal, Reich, Mech; In-situ Raman and Photoluminescence of Gamma Irradiated Silica Fibers; (U) 10/13/93. (UNCLASSIFIED)

21. Bock, Urbanczyk, Voet; Performance Analysis of Fiber-optic Concrete Stress Sensors in Polarimetric and White-light Interferometric Configurations Applicable to Nuclear Facilities; (U) 10/1794. (UNCLASSIFIED)

22. Bodette, Brannon; Evaluation of Fiber Performance in the ACRR; (U) 7/27/92. (UNCLASSIFIED)

23. Boeder, Adams, Nickerson; Scintillating Fiber Detector System for Spacecraft Dosimetry; (U) 9/13/93. (UNCLASSIFIED)

24. Boeder; Fiber-Optic Nuclear Detector System Technical Description Production Version 1993-FND-C2; (U) 7/1/93. (UNCLASSIFIED)

25. Boisde, Carvalho, Dumas, Neuman; Fluoresence Emmission by Molecular Impurities in Irradiated and Non-Irradiated Silica; (U) 8/22/84. (UNCLASSIFIED)

26. Brambani, Friebele, Askins, Gingerich, Onstott; Radiation Effects in Polarization-Maintaining Fibers; (U) 9/6/88. (UNCLASSIFIED)

27. Brannon, Bodette, McArthur; The Infrared Transmission of Low-OH Fibers While Exposed to Nuclear Radiations; (U) 07/92. (UNCLASSIFIED)

28. Brannon; Transient Radiation-Induced Absorption at 1061 nm in $LiNbO_3$ and $MgO:LiNbO_3$; (U) 01/18/94. (UNCLASSIFIED)

29. Braunig, Fritsch, Lehmann, Barry; Radiation-induced Displacement Damage in Silican Carbide Blue Light-Emitting Diodes; (U) 9/9/91. (UNCLASSIFIED)

30. Breuze', Serre; Gamma-ray Vulnerability of Light-emitting Diodes, Injection-laser Diodes and PIN-photodiodes for 1.3 um-wavelength Fiber Optics. (UNCLASSIFIED)

31. Breuze, Serre, Colas, Garnero, Hamet; Affaiblissement et aux d'Erreur de Transmission de Fibres OptiquesMultimodes soumises a une Irradiation Gamma de Faible Debit de Dose; (U) 9/13/93. (UNCLASSIFIED)

32. Bueker, Haesing, Gerhard; Compensation of Fading Effects of Radiation Induced Loss by Multiple Wavelength Measurements. (UNCLASSIFIED)

33. Bueker; Fiber-optic Radiation Sensors; (U) 10/17/94. (UNCLASSIFIED)

34. Carson, Chow; Neutron Effects in High-Power GaAs Laser Diodes; (U) 12/89. (UNCLASSIFIED)

35. Carson; Radiation Effects in Semiconductor Laser Diode Arrays. (UNCLASSIFIED)

36. Cases, Griscom, Tran; Radiation Effects in ZrF4 Based Glasses I. Electron Spin Resonance; (U) 5/13/84. (UNCLASSIFIED)

37. Chen, McNulty, Abdel-Kader, Miller, Thompson; Single and Multiple Proton-Induced Niel Events in Silicon. (UNCLASSIFIED)

38. Chen, McNulty, Larson, Thompson, Miller, Lee; Dark Current Induced in Large CCD Arrays by Proton-Induced Elastic Reactions and Single to Multiple-event Spallation Reactions. (UNCLASSIFIED)

39. Coenen, Decreton, Liesenborgs; Gamma Irradiation Facilities at SCK/CEN Testing of Sensors, Electronics and Optical Components for Remote Handling Systems; (U) 05/20/92. (UNCLASSIFIED)

40. Coenen, Decreton; Feasibility of Optical Sensing for Robotics in Highly Radioactive Environments; (U) 08/01/93. (UNCLASSIFIED)

41. Coenen, Decreton; Gamma Ray Radiation Effects in Optical Fibers and Optoelectronic Components; (U) 12/31/1991. (UNCLASSIFIED)

42. Coic, Musseau, Leray; A Study of Radiation Vulnerability of Ferroelectric Material and Devices; (U) 06/94. (UNCLASSIFIED)

43. Crabtree, LaBel, Stassinopoulos, MillerPreliminary Analysis of the SAMPEX MIL-SD-1773 Spaceflight Data. (UNCLASSIFIED)

44. Cross, Fritz, Haakenson, Hoeflein, Hughes, Kelnhofer, Lamm, Summerhays; The Boeing Photonics Space Experiment; (U) 4/13/93. (UNCLASSIFIED)

45. Dale, Chen, Marshall, McNulty; A Comparison of Monte Carlo and Analytic Treatments of Displacement Damage in Si Microvolumes. (UNCLASSIFIED)

46. Dale, Chen, McNulty, Marshall, Burke; A Comparison of Monte Carlo and Analytic Treatments of Displacement Damage in Si Microvolumes; (U) 07/94. (UNCLASSIFIED)

47. Dale, Marshall, Cimmungs, Shamey; Displacement Damage Effects in Mixed Particle Environments for Shielded Spacecraft CCDs. (UNCLASSIFIED)

48. Dale, Marshall; Radiation Response of 1300 nm Optoelectronic Components in a Natural Space Environment; (U) 7/1/92. (UNCLASSIFIED)

49. De Jong; Optical Fibers Irradiated with 3800 RADs X- or Gamma-rays Show Large Attenuation Differences; (U) 1987. (UNCLASSIFIED)

50. Decreton, Massaut, Borgermans; Potential Benefit of Fiber Optics in Nuclear Applications, The Case of Decommissioning and the Waste Storage Activities; (U) 10/17/94. (UNCLASSIFIED)

51. Decreton; Viewing Systems in the Fusion Reactor Vessel Radiation Hardened Glasses up to 300 MGy; 08/22/94. (UNCLASSIFIED)

52. Dianov, Golant, Karpov, Khrapko, Kurkov,Mashinsky, Protopopov; Fluorine-doped Silica Optical Fibers Fabricated Using Plasma-chemical Technologies; (U) 10/17/94. (UNCLASSIFIED)

53. Dianov, Golant, Khrapko, Mashinsky, Neustruev, Sazhin, Guryanov, Gusovsky, Miroshnichenko; Radiation Resistance of Optical Fibers with Fluorine-doped Silica Cladding; (U) 10/17/94. (UNCLASSIFIED)

54. Dianov, Kornienko, Rybaltovskii, Chernov; Unstable Radiation Color Centers in Pure Silica Fibers: the Nature and Properti; (U) 10/17/94. (UNCLASSIFIED)

55. Dimiduk, O'Reilly; Electron Irradiation of InGaAsP LEDs and InGaAs Photodetectors; (U) 9/25/86. (UNCLASSIFIED)

56. Dreute, Rocher, Heinrich, Harboe--Sorenson, Adams, SchardtStudy of SEUs Generated by High Energy Ions. (UNCLASSIFIED)

57. Ediriweera, KvasnikSpectral Measurements in Gamma Irradiated Optical Fibers Using Attenuation and Raman Spectroscopy. (UNCLASSIFIED)

58. Ellis, Johnson; PCS Cable Connector Termination, Radiation Exposure, and Testing; (U) 8/22/84. (UNCLASSIFIED)

59. Evans, Gossett, Hager, Hong, HughlockEffects of 5.5 MeV Proton Irradiation on Reliability of a Strained Quantum-well Laser diode and a Multiple Quantum-well Broad-band Light-emitting Diode. (UNCLASSIFIED)

60. Evans, Hager, Hughlock, 5.5 MeV Proton Irradiation of a Strained Quantum-Well Laser Diode and a Multiple Quantum-Well Broad-band LED. (UNCLASSIFIED)

61. Evans, Hager, Hughlock; Space-environment Simulation Studies by MeV Proton Irraditation of Two New Quantum-well Based Fiber-optic Light Sources; Evans, Hager, Hughlock; (U) 4/13/93. (UNCLASSIFIED)

62. Evans, Maida and Varshneya; Radiation Effects in Multimode, Step Index Fiber Optic Delay Lines at 1300 nm; (U) 9/1/89. (UNCLASSIFIED)

63. Evans, Sigel; Radiation Resistant Fiber Optic Materials and Waveguides; (U) 12/15/75. (UNCLASSIFIED)

64. Evans; Survivability of Quantum-Well Optoelectronic Devices for Space Applications; (U) 04/04/94. (UNCLASSIFIED)

65. Evans; The Use of Hydrogen as a Radiation Protection Agent at Low Temperature in a Low-OH, Pure Silica Core Optical Fiber. (UNCLASSIFIED)

66. Evans; Thresholds for Photoenhanced Radiation Resistance in Optical Fibers; (U) 9/1/89. (UNCLASSIFIED)

67. Fabian, Grzesik, Klein; Producing Radiation Hard All Silica Fibers - State of the Art and Future Aspects; (U) 10/4/90. (UNCLASSIFIED)

68. Fabian, Grzesik, Worner, Henschel, Kohn, SchmidtRadiation Resistance of Optical Fibers, Correlation between UV-Attenuation and Radiation Induced Loss. (UNCLASSIFIED)

69. Falter, McElhaney, Simpson; Development of Detectors for Waste Tank Characterization; (U) 12/06/91. (UNCLASSIFIED)

70. Ferdinand, Magne, Marty, Rougeault, Bernage, Douay, Fertein, Lahoreau, Niay, Bbayon, Georges, Monerie; Optical Fiber Bragg Sensors for Structure Monitoring within Nuclear Power Plants; (U) 10/17/94. (UNCLASSIFIED)

71. Fischer; Pulsed Irradiation Response of a Radiation Hardened Silicon Photodiode Incorporating a Sinker Diffusion. (UNCLASSIFIED)

72. Friebele, Askins, Gingerich, Long; Optical Fiber Waveguides in Radiation Environments, II. (UNCLASSIFIED)

73. Friebele, Askins, Long, Gingerich; Radiation Effects in Optical Communications Systems: Fibers Exposed at Low Rates and Selfoc Lenses; (U) 1/25/84. (UNCLASSIFIED)

74. Friebele, Askins, Shaw, Gingerich, Harrington, Griscom, Tsai, Paek, Schmidt; Correlation of Single-mode Fiber Radiation Response and Fabrication Parameters; (U) 5/20/91. (UNCLASSIFIED)

75. Friebele, Brambani, Gingerich, Hickey, Onstott; Radiation-Induced Attenuation in Polarization-Maintaining Fibers: Low Dose Rate Response, Stress and Materials Effects. (UNCLASSIFIED)

76. Friebele, et al; Report of the 1991 Meeting of the Nuclear Effects Task Group NATO Panel 4, Research Study Group .12; (U) 9/16/91. (UNCLASSIFIED)

77. Friebele, Gingerich, Brambani, Harrington, Hickey, Onstott; Radiation Effects in Polarization-Maintaining Fibers; (U) 4/24/90. (UNCLASSIFIED)

78. Friebele, Gingerich, GriscomExtrapolating Radiation-Induced Loss Measurements in Optical Fibers from the Laboratory to Real World Environments. (UNCLASSIFIED)

79. Friebele, Gingerich, Hickey, Harrington, Kalomiris; Radiation Effects in High NA Single Mode Optical Fibers. (UNCLASSIFIED)

80. Friebele, Gingerich, Hickey, Kalomiris; Radiation Effects in Bend-Resistent Optical Fibers; (U) 3/20/90. (UNCLASSIFIED)

81. Friebele, Gingerich, Long, Levin, Pinnow; Radiation-Resistant Low OH Content Silica Core Fibers; (U) 09/83. (UNCLASSIFIED)

82. Friebele, Gingerich, Long; Radiation Damage of Optical Fiber Waveguides at Long Wavelengths; (U) 02/01/82. (UNCLASSIFIED)

83. Friebele, Gingerich; Photobleaching Effects in Optical Fiber Waveguides; (U) 10/01/81. (UNCLASSIFIED)

84. Friebele, Gingerich; Testing of Fibers in Radiation Environments; 12/23/91. (UNCLASSIFIED)

85. Friebele, Long, Askins, Gingerich, Marrone, Griscom; Overview of Radiation Effects in Fiber Optics; (U) 1985. (UNCLASSIFIED)

86. Friebele, Long, Askins, Gingerich; Radiation Response of Optical Fibers and Selfoc Lenses at 1.3 μm; (U) 8/22/84. (UNCLASSIFIED)

87. Friebele, Lyons, Blackburn, Henschel, Johan, Krinsky, Robinson, Schneider, Smith, Taylor; Interlaboratory Comparison of Radiation-Induced Attenuation in Optical Fibers. Part III: Transient Exposures; (U) 1/10/90. (UNCLASSIFIED)

88. Friebele, Schultz, Gingerich; Compositional Effects on the Radiation Response of Ge-Doped Silica-Core Optical Fiber Waveguides; (U) 09/01/80. (UNCLASSIFIED)

89. Friebele, Taylor, De Beauregard, Wall, Barnes; Interlaboratory Comparison of Radiation-Induced Attenuation in Optical Fibers. Part I: Steady-State Exposures; (U) 2/2/88. (UNCLASSIFIED)

90. Friebele, Taylor; Standardized Testing of the Radiation Response of Optical Fibers; (U) 3/20/90. (UNCLASSIFIED)

91. Friebele, Tran; Radiation Effects in ZrF4 Based Glasses II. Optical Absorption; (U) 10/8/84. (UNCLASSIFIED)

92. Friebele; Effect of Nuclear Radiation on Selfoc Micro lenses; (U) 9/1/83. (UNCLASSIFIED)

93. Friebele, Gingerich, Griscom; Survivability of Optical Fibers in Space; (U) 12/31/92. (UNCLASSIFIED)

94. Gingerich, Dorsey, Askins, Friebele; A Comparison of Gamma, Neutron and Proton Irradiations of Multimode Fibers; (U) 5/21/87. (UNCLASSIFIED)

95. Greenwell, Barnes, Scott, Biswas; Optical Fibers in the Adverse Space Environment: A Critical Assessment of Optical fibers for the Space Station; (U) 3/20/90. (UNCLASSIFIED)

96. Greenwell, Barnes, Scott, Biswas; Optical Fibers in the Adverse Space Environment: The Space Station; (U) 4/25/90. (UNCLASSIFIED)

97. Greenwell, Barnes; Current Status of Radiation Effects Knowledge for Fiber Based Systems and Associated Components. (UNCLASSIFIED)

98. Greenwell, Lyons; Development of Radiation Test Procedures for Fiber Systems; (U) 3/1/90. (UNCLASSIFIED)

99. Greenwell, Saggese, Hatch; The Use of Remote Fiber Optic Spectroscopic Instrumentation to Characterize Nuclear Waste; (U) 05/01/95. (UNCLASSIFIED)

100. Greenwell, Saggese; The Development of ASTM Test Procedures to Measure Induced Ionizing Radiation Effects in Broadband and Remote Raman Fiber Optic Spectroscopic Systems; (U) 10/17/94. (UNCLASSIFIED)

101. Greenwell, Scott, Chapman, Mattison; Radiation Testing of Optical Fibers for the Space Station; (U) 9/9/91. (UNCLASSIFIED)

102. Greenwell, Scott, Karbassiyoon, Hodges; Radiation Testing of Single Mode Fibers at 1500 nm; (U) 9/5/89. (UNCLASSIFIED)

103. Greenwell, Scott, McAlarney; Nuclear Survivable Polarization Fibers For Fiber Gyroscopes on Spacecraft; (U) 9/9/92. (UNCLASSIFIED)

104. Greenwell; Reliable Fiber Optics for the Adverse Nuclear Environment; (U) 6/1/91. (UNCLASSIFIED)

105. Griffin, Kelly, Luera, Barry, Lazo; Neutrons Damage Equivalence in GaAs; (U) 7/15/91. (UNCLASSIFIED)

106. Griscom, Gingerich, Friebele, Putnam, Unruh; Evaluation of Fast-Neutron Radiation Effects in Optical Fibers for Fusion Reactor Diagnostics; (U) 12/1/92. (UNCLASSIFIED)

107. Griscom, Gingerich, Friebele; Model for the Dose, Dose-Rate and Temperature Dependence of Radiation-Induced Loss in Optical Fibers; (U) 6/94. (UNCLASSIFIED)

108. Griscom, Gingerich, Friebele; Radiation-Induced Defects in Glasses: Origin of Power-Law Dependence of Concentration on Dose; (U) 08/16/93. (UNCLASSIFIED)

109. Griscom, Tran; Chlorine-Associated Defect Centers in Irradiated ZrF Based Glasses; (U) 6/15/84. (UNCLASSIFIED)

110. Gutierrez, Swift, Dubovitsky, Bartman, Barnes, Dorsky; Polarization Dependent Effects of Radiation on Wavelength Division Multiplexers; (U) 07/26/94. (UNCLASSIFIED)

111. Gutierrez, Swift,Dubovitsky, Bartman, Barnes; Radiation Effects on Fused Biconical Taper Wavelength Division Multiplexers; (U) 07/94. (UNCLASSIFIED)

112. Gutierrez,Swift, Barnes, Johnston, McLandrich; Proton Irradiation Test of WDM Couplers; (U) 01/11/94. (UNCLASSIFIED)

113. Gutierrez; Fiber Optic Rotation Sensor (FORS); Results of Gamma-Irradiation Testing on Fujikura Polarization Maintaining (PM) Fibers; (U) 8/13/92. (UNCLASSIFIED)

114. Hartmayer, Jackson, Johnston; Space Environment Effects on Optical Cables; Hartmayer, Jackson, Johnston; (U) 4/13/93. (UNCLASSIFIED)

115. Hatch; Change in FWHM of AlGaAs LEDs Subjected to Mixed Neutron and Gamma Radiation; (U) 07/26/94. (UNCLASSIFIED)

116. Henschel, Kohn, Schmidt, Bawirzanski, Landers; Optical Fibers for High Radiation Dose Environments. (UNCLASSIFIED)

117. Henschel, Kohn, Schmidt, Rittich; Contribution of Butt-Joint Connectors and Lens Connectors to the Radiation Induced Loss of Optical Fiber Cables at 1300 nm Wavelength; (U) 9/9/91. (UNCLASSIFIED)

118. Henschel, Kohn, Schmidt; Optical Fibers as Radiation Dosimeters; (U) 6/10/91. (UNCLASSIFIED)

119. Henschel, Kohn, Schmidt; Radiation Damage and Radiation Induced Loss in Optical Fibers; (U) 9/1/89. (UNCLASSIFIED)

120. Henschel, Kohn, Schmidt; Radiation Induced Loss Measurement of Optical Fibers with Optical Time Domain Reflectometers (OTDR) at High and Low Dose Rates; (U) 9/9/91. (UNCLASSIFIED)

121. Henschel, Kohn, Schmidt; Radiation Induced Transmission Loss of Integrated Optic Waveguide Devices; (U) 9/6/88. (UNCLASSIFIED)

122. Henschel, Kohn, Schmidt; Radiation Sensitivity of Fiber Optic Couplers. (UNCLASSIFIED)

123. Henschel, Kohn, Schmidt; Radiation Sensitivity of Passive Components of Fiber Optic Data Transfer and Sensor Systems; (U) 10/17/94. (UNCLASSIFIED)

124. Henschel, Kohn; Contribution of the Fraunhofer-INT to the 1994 Meeting of the Nuclear Effects Task Group NATO Panel IV Research Study Group 12; (U) 10/47/94. (UNCLASSIFIED)

125. Henschel; Radiation Hardness of Present Optical Fibers; (U) 10/17/94. (UNCLASSIFIED)

126. Herman, Rose, Kanofsky; System Implications of Radiation-Induced Long Term Transients in High Speed Optical Receivers; (U) 9/1/89. (UNCLASSIFIED)

127. Hickernell, Sanford, Christensen; Issues Affecting the Characterization of Integrated Optical Devices Subjected to Ionizing Radiation; (U) 9/18/90. (UNCLASSIFIED)

128. Hines, Dale, Stapor; Ionizing Space Radiation Effects on Surface Acoustic Wave Resonators. (UNCLASSIFIED)

129. Holcomb, Antonescu; A Review of Potential Uses for Fiber Optic Sensors in Nuclear Power Plants with Attendant Benefits in Plant Safety and Operational Efficiency; (U) 10/25/93. (UNCLASSIFIED)

130. Holcomb, Hatch, Miller, Shao, Talnagi; Optical Fibers in Nuclear Reactor Radiation Environments. (UNCLASSIFIED)

131. Hopkins, Hopkinson, Johlander; Proton-Induced Charge Transfer Degradation in CCDs for Near Room Temperature Applications. (UNCLASSIFIED)

132. Hopkins, Hopkinson, Johlander; Proton-Induced Charge Transfer Degradation in CCDs for Near-room Temperature Applications; (U) 07/24/94. (UNCLASSIFIED)

133. Hopkins, Kelly, Looney, Lyons; Transient Attenuation in Optical Fibers; (U) 8/19/84. (UNCLASSIFIED)

134. Hopkinson, Baddiley, Guy, Parsons; Total Dose and Proton Testing of a Commercial HgCdTe Array. (UNCLASSIFIED)

135. Hopkinson; Proton Damage Effects in an EEV CCD Imager; (U) 12/89. (UNCLASSIFIED)

136. Hum, Barry; Radiation Damage Constants of Light-Emitting Diodes by a Low-Current Evaluation Method; (U) 12/75. (UNCLASSIFIED)

137. Iida, Ire, Sumita, Matsubara, Heikkinen, Short; Fusion Neutron Damage on Optical Fibers and Optoelectronic Devices; (U) 2/15/88. (UNCLASSIFIED)

138. Iida, Sumita, Logan; Fusion Neutron Irradiation Test for Optical Fibers and Optoelectronic Devices; (U) 6/23/83. (UNCLASSIFIED)

139. Inoue, Koike, Imada; Development of the Nuclear Optical Penetration; (U) 8/22/84. (UNCLASSIFIED)

140. Johan, Charre; Pulsed X-Ray Induced Attenuation Measurement of Single Mode Optical Fibers and Coupler Materials; (U) 9/13/93. (UNCLASSIFIED)

141. Johnston, Caldwell; Design Technoligies for Hardening Fiber Optic Receivers; (U) 12/1/80. (UNCLASSIFIED)

142. Jolly, Vicery; Modelling Threshold Shift of Power Laser Diodes Under Neutronic and Photonic Irradiation; (U) 07/94. (UNCLASSIFIED)

143. Jucker, Breuze, Berghmans, Decreton; Radiation Tolerant Fiber-Optic Transmission and Sensing for Use in Remote Systems in Nuclear Power Plant, Dismantling and Fusion Applications; (U) 10/17/94. (UNCLASSIFIED)

144. Kakuta, Wakayama, Sanada, Fukuda, Inada, Suematsu, Yatsuhashi; Radiation Resistance Characteristics of Optical Fibers; (U) 3/28/86. (UNCLASSIFIED)

145. Kanofsky, Gershman, RosenRadiation Effects on the Components of Optical LAN Systems. (UNCLASSIFIED)

146. Kanofsky, HermanRadiation Effects on Polymer Waveguides. (UNCLASSIFIED)

147. Kanofsky, Minford, Watson; Radiation Effects on Dynamical Behavior of LiNbO3 Switching Devices; (U) 4/9/91. (UNCLASSIFIED)

148. Kanofsky, Minford; Radiation Effects on Proton Exchange Waveguides. (UNCLASSIFIED)

149. Kanofsky, Spector, Remke, Witmer; Radiation Effects on GaAs Optical System FET Devices; (U) 4/1/91. (UNCLASSIFIED)

150. Karbassiyoon, Grenwell, Scott, Spencer; Radiation Effects on Bend Insensitive Fibers at 1300 and 1550 nm; (U) 9/18/90. (UNCLASSIFIED)

151. Karbassiyoon,Moras, Greenwell, Scott; Radiation Testing of ALCATEL FOG-V Bend Insensitive Single Mode Fiber; (U) 3/20/90. (UNCLASSIFIED)

152. Korde, Cable, Canfield; 100% Internal Quantum Efficiency Silicon Photodiodes with one G-RAD Passivating Dioxide. (UNCLASSIFIED)

153. Krinsky, Reddy; Ionizing Radiation-Induced Attenuation in Optical Fibers at Multiple Wavelengths and Temperature Extremes; (U) 9/18/90. (UNCLASSIFIED)

154. LaBel, Cooley, Stassinopoulos, Marshall, Crabtree; Single Event Test Methodology for Integrated Optoelectronics. (UNCLASSIFIED)

155. LaBel, Flanegan, Marshall, Dale, Stassinopoulos; Spaceflight Experiences and Lessons Learned with NASA's First Fiber Optic Data Bus; (U) 1994. (UNCLASSIFIED)

156. LaBel, Hawkins, Cooley, Crabtree, Marshall, Dale, Gates, Kim, Stassinopoulos; Single Event Effect Ground Test Results for a Fiber Optic Data Interconnect and Associated Electronics. (UNCLASSIFIED)

157. LaBel, Marshsll, Dale, Stassinopoulos, Johnston, Crabtree, Kim; Single Event Effects on Associated Electronics for Fiber Optic Systems; (U) 04/05/94. (UNCLASSIFIED)

158. LaBel, Stassinopoulos, Brucker; Transient SEUS in a Fiber Optic System for Space Applications; (U) 9/9/91. (UNCLASSIFIED)

159. LaBel, Stassinoupoulos, Marshall, Petersen, Dale, Crabtree, Stauffer; Proton Irradiation SEU Test Results for the SEDS MIL-STD-1773 Fiber Optic Data Bus: Integrated Optoelectronics; (U) 4/13/93. (UNCLASSIFIED)

160. Larkin, Averianov, Dedushenko, Likhachev, Mamaeu, Zouari; Optical Fiber Links in Nuclear Physics Experiments; (U) 10/17/94. (UNCLASSIFIED)

161. Leskovar; Optical Data Transmission at the Superconducting Super Collider. (UNCLASSIFIED)

162. Leskovar; Optical Data Transmission Systems in Radiation Environment; (U) 05/89. (UNCLASSIFIED)

163. Leskovar; Optical Receivers for Wide Band Data Transmission Systems; (U) 02/89. (UNCLASSIFIED)

164. Lischka, Clemens, Henschel, Kohn, Lennartz, Schmidt; Radiation Effects in Optoelectronic Devices; (U) 10/17/94. (UNCLASSIFIED)

165. Lischka, Henschel, Kohn, Lennartz, Schmidt; Radiation Effects in Light Emitting Diodes, Laser Diodes, Photodiodes, and Optocouplers; (U) 9/13/93. (UNCLASSIFIED)

166. Lischka, Henschel, Lennartz, Schmidt; Radiation Sensitivity of Light Emitting Diodes (LED), Laser Diodes (LD) and Phtodiodes (PD); (U) 9/9/91. (UNCLASSIFIED)

167. Liu, Johnston; Theory of Radiation-Induced Absorption in Optical Fibers; (U) 1994. (UNCLASSIFIED)

168. Lockwood, Bishop, Selph; Measurements of Pulsed Radiation-Induced Fiber Fluorescence and Darkening; (U) 07/26/94. (UNCLASSIFIED)

169. Looney, Forman, Marshall, Shaub; Observed Phase Shift due to Radiation Exposure in Optical Fibers. (UNCLASSIFIED)

170. Looney, Lyons, Schneider, Henschel; Influence of Preform Variations and Drawing Conditions on Transient Radiation Effects in Pure Silica Fibers; (U) 9/21/86. (UNCLASSIFIED)

171. Looney, Lyons; Measurement of Radiation Induced Attenuation in Optical Fibers by Optical Time Domain Reflectometry; (U) 4/1/91. (UNCLASSIFIED)

172. Lyons, Looney, Henschel, Kohn, Schmidt, Klein, Fabian, Mils, Nelson; Influence of Preform and Draw Conditions on UV Transmission and Transient Radiation Sensitivity of an Optical Fiber; (U) 9/5/89. (UNCLASSIFIED)

173. Lyons, Looney, Klein, Fabian, Mills, Henschel, Nelson; Influence of Preform and Draw Conditions on UV Transmission and Transient Radiation Sensitivity of an Optical Fiber; (U) 9/10/89. (UNCLASSIFIED)

174. Lyons, Looney; Enhanced Radiation Resistance of High-OH Silica Optical Fibers. (UNCLASSIFIED)

175. Lyons, Looney; Radiation Induced Attenuation of High-OH Optical Fibers after Hydrogen Treatment in the Presence of Ionizing Radiation; (U) 9/9/91. (UNCLASSIFIED)

176. Lyons, Looney; Transient Radiation Effects in Polarization-Maintaining Fibers; (U) 12/31/92. (UNCLASSIFIED)

177. Lyons; Fiber Optics in Transient Radiation Fields; (U) 1985. (UNCLASSIFIED)

178. Lyons; Radiation-Induced Transient Absorption: Interlaboratory Calibration of Single Mode Fibers; (U) 4/17/89. (UNCLASSIFIED)

179. Lyons; Report of the Nuclear Effects Task Group, NATO Panel 4, Research Study Group 12; (U) 9/18/89. (UNCLASSIFIED)

180. Lyons; Review of High Bandwith Fiber Optic Radiation Sensors; (U) 8/18/85. (UNCLASSIFIED)

181. Marshall, Dale, Carts, LaBel; Particle-Induced Bit Errors in High Performance Fiber Optic Data Links for Satellite Data Management. (UNCLASSIFIED)

182. Marshall, Dale, Carts, LaBel; Space Radiation Effects in High Performance Fiber Optic Data Links for Satellite Data Management Applications. (UNCLASSIFIED)

183. Marshall, Dale, Friebele, LaBel; Survivable Fiber Based Data Links for Satellite Radiation Environments; (U) 9/8/93. (UNCLASSIFIED)

184. Marshall, Dale, LaBel; Charged Particle Effects on Optoelectronic Devices and Bit Error Rate Measurement on 400 Mbs Fiber Based Data Links; (U) 6/94. (UNCLASSIFIED)

185. Marshall, Dale, Martin, Carts, LaBel; Test Results and Calculations of Ion-Induced Bit Error Rates for Fiber-Based Data Links in Orbital Satellite Environments. (UNCLASSIFIED)

186. Marshall, LaBel, Dale, Bristow, Petersen, Stassinopoulos; Physical Interaction Between Charged Particles and Optoelectronic Devices and the Effects on Fiber Based Data Links; (U) 4/13/93. (UNCLASSIFIED)

187. Matejec, Pospisilova, Darickova, Vanickova; Attenuation of Silica Optical Fibers in Nuclear Environment and Its Dependence on the Properties of Materials for Fiber Preparation; (U) 10/17/94. (UNCLASSIFIED)

188. Mattern, Watkins, Skoog, Barsis; Absorption Induced in Optical Waveguides by Pulsed Electrons as a Function of Temperature, Low Dose Rate Gamma and Beta Rays, and 14MeV Neutrons; (U) 12/75. (UNCLASSIFIED)

189. Matzen, Hawthorne, Kilian; Radiation-Hardened Phototransistor; (U) 7/15/91. (UNCLASSIFIED)

190. McElhaney, Falter, Todd, Simpson, Mihalczo; Passive (Self-Powered) Fiber-Optic Sensors; (U) 10/27/92. (UNCLASSIFIED)

191. McKnight, Dueber, Taylor; Space Debris and Micrometeorite Events Experienced by WL Experiment 701 in Prolonged Low Earth Orbit; (U) 06/01/91. (UNCLASSIFIED)

192. Meshel, Lum, Marshall; Radiation Hardness Assurance Characterization Testing of InGaAsP Fiber Optic Transmitter and Receiver Modules. (UNCLASSIFIED)

193. Mies, Soto; Characterization of the Radiation Sensitivity of Single-mode Optical Fibers; (U) 10/01/85. (UNCLASSIFIED)

194. Miller, Holcomb, Shao, Talnagi, Hatch; Optical Fibers in Radiation Environments; (U) 2/15/92. (UNCLASSIFIED)

195. Miller, Thompson, Howe, Lee, Philbrick, Erhardt; Ionizing Radiation Impact on Performance of Two Phase Linear CCD Arrays. (UNCLASSIFIED)

196. Moss, Casperson, Echave, Edwards, Miller, Saylor, Sweet, Valencia; A Space Fiber-Optic X-Ray Burst Detector. (UNCLASSIFIED)

197. Murowinski, Gao, Deen; Effects of Space Radiation Damage and Temperature on CCD Noise for the Lyman FUSE Mission; (U) 4/13/93. (UNCLASSIFIED)

198. Negre, Ducrocq; Radiation-Induced Attenuation in Detectors Using Cerenkov Radiator or Plastic Scintillator; (U) 04/05/94. (UNCLASSIFIED)

199. Nelson, Brownlow, Cohen, Dimarcello, Huff, Krause, Lemaire, Reed, Shenk, Sigety, Simpson, Tomita, Walker; The Fabrication and Performance of Long Lengths of Silica Core Fiber; (U) 05/30/85. (UNCLASSIFIED)

200. Nelson; High Pressure Fiber Optic Sensor for Nuclear Test Instrumentation Phase II; (U) 04/91. (UNCLASSIFIED)

201. Newberry; Investigation of Single Event Effects at the System Level; (U) 7/1/89. (UNCLASSIFIED)

202. Obara, Kakudate, Oka, Tada, Morita, Seki; Development of Optical Components for In-vessel Viewing Systems Use for Fusion Experimental Reactor; (U) 10/17/94. (UNCLASSIFIED)

203. Ohyama, Vanhellemont, Sunaga, Poortmas, Caymax, Clauws; On the Degradation of 1-MeV Electron Irradiated $S_{1-x}Ge_x$ Diodes; (U) 06/94. (UNCLASSIFIED)

204. Okamoto, Ohnishi, Shintani, Iri, Hirashima, Hayashi, Tanaka, Morishita; Radiation Response of Pure-silica Core Fiber and Image guide in High Radiation Field; (U) 12/20/83. (UNCLASSIFIED)

205. Padden, Taylor, Sanchez, Berry, Chapman, DeWalt, Wong; LiTa03 and LiNb03:Ti Response to Ionizing Radiation; (U) 2/1/91. (UNCLASSIFIED)

206. Partin; Fiber Optics in High Dose Rate Fields; (U) 1985. (UNCLASSIFIED)

207. Partin; Radiation Response of Optical Fibers in a Nuclear Reactor; (U) 8/1/84. (UNCLASSIFIED)

208. Paxton, Adair; A Comparative Evaluation of Selected Radiation Resistant Fibers Suitable for Possible Shipboard Applications; (U) 04/83. (UNCLASSIFIED)

209. Paxton; Nuclear Radiation Effects on Optical Fiber; (U) 09/02/82. (UNCLASSIFIED)

210. Pirich, Stauber, DeCarlo; Effect of Weakly and Strongly Ionizing Radiation on the Optical, Infrared, and Dielectric Properties of Porous Sol-gel Glasses; (U) 07/29/94. (UNCLASSIFIED)

211. Polimadei, Share, Epstein, Lynch, Sullivan; Performance of $Ga_{1-x}Al_xAs$ Light Emitting Diodes in Radiation Environments; (U) 12/74. (UNCLASSIFIED)

212. Poret, Suter; A Theoretical Study of Ionizing Radiation Effects on Optical Fiber Parameters; (U) 1994. (UNCLASSIFIED)

213. Ritter; Microelectronics and Photonics Test Bed; (U) 4/13/93. (UNCLASSIFIED)

214. Robinson; Ionizing Radiation Effects on Doped Silica and Pure Silica Core Fibers; (U) 9/25/86. (UNCLASSIFIED)

215. Roeske, Jander, Lancaster, Lowry, McWright, Peterson, Tindall; Preliminary Radiation Hardness Testing of LiNbO3:Ti Optical Directional Coupler Modulators Operating at 810 nm; (U) 5/21/87. (UNCLASSIFIED)

216. Rogina; Radiation Testing of PCS Optical Fiber for Dose Level Sensor Application; (U) 10/11/94. (UNCLASSIFIED)

217. Rotter and Jander; Measuring Transient Radiation Effects in Optical Fibers; (U) 8/1/84. (UNCLASSIFIED)

218. Saggese, Greenwell; Standards Development for Fiber Optic Spectroscopic Components for Adverse Environments; (U) 07/26/94. (UNCLASSIFIED)

219. Saggese, Greenwell, Reich, Mech, Bilodeau; Evaluation of Fiber Optic Sensors for Nuclear Waste Tank Environments; (U) 10/17/94. (UNCLASSIFIED)

220. Schneider, Babst; Radiation-Induced Light Emission in Silica Core Fibers; (U) 8/22/84. (UNCLASSIFIED)

221. Schneider; Radiation Sensitivity of Thick Core All-Glass Fibers in Reactor Radiation Fields; (U) 9/2/82. (UNCLASSIFIED)

222. Schulte; Radiation Effects on Undersea Lightguide Cables; (U) 02/11/85. (UNCLASSIFIED)

223. Scott, Barnes, Greenwell; Gamma Induced Attenuation in Polarization Maintaining and Single Mode Fibers; (U) 9/1/89. (UNCLASSIFIED)

224. Scott, McAlarney, Greenwell; Induced Attenuation and Polarization Hold Properties in ECore Fibers after Co-60 Irradiation; (U) 07/18/94. (UNCLASSIFIED)

225. Scott; The Radiation Sensitivity of an Elliptical Core Polarization Maintaining Fiber; (U) 9/8/92. (UNCLASSIFIED)

226. Shute, Shang; Optical Fibers for Tethered Vehicle Applications; 3/20/90. (UNCLASSIFIED)

227. Sigel, Friebele, Gingerich, Hayden; Radiation Response of Large Core Polymer Clad Silica Optical Fibers; (U) 12/6/79. (UNCLASSIFIED)

228. Sigel; Fiber Transmission Losses in High-Radiation Fields; (U) 5/22/80. (UNCLASSIFIED)

229. Singh, Banerjee, Mitra; Neutron Irradiation Effects on Fibers Operating at 1.3 μm and 1.55 μm; (U) 9/18/90. (UNCLASSIFIED)

230. Skutnik, Scott; Radiation Behavior of Pure Silica Core Optical Fiber; (U) 9/1/89. (UNCLASSIFIED)

231. Smiley, Whitcomb, Peressini, Whitaker, Flurer, Colburn, Lyons, Ogle, Looney; Optical Characteristics of Radiation Resistant Fibers; (U) 8/22/84. (UNCLASSIFIED)

232. Smith, Hugenberg, Flatley, GarrettTransient Radiation Effects in Annealed Proton Exchange LiNb03 and LiTaO3 Waveguides. (UNCLASSIFIED)

233. Smith, Jander, Roeske; Optical Fiber Radiation-Damage Measurements; (U) 9/25/86. (UNCLASSIFIED)

234. Society of Automotive Engineers (SAE) Aerospace Information Report (AIR), MIL-STD 1773 USERS HANDBOOK, Chapter 8, Radiations Effects; AS3A-4B Working Group; (U) 7/24/92. (UNCLASSIFIED)

235. Soda, Barnes, Kiehl; The Effect of Gamma Irradiation on Optical Isolators; (U) 12/75. (UNCLASSIFIED)

236. Spector, McCollum, Spowart; Advances in Lithium-Loaded Glass Scintillator Fiber Development; (U) 10/08/91. (UNCLASSIFIED)

237. Spector, McCollum, Spowart; Advances in Terbium-Doped Lithium-Loaded Scintillator Glass Development; (U) 07/15/92. (UNCLASSIFIED)

238. Spector, McCollum, Spowart; Improved Terbium-Doped Lithium-Loaded Glass Scintillator Fibers; (U) 11/06/92. (UNCLASSIFIED)

239. Spector, McCollum, Spowart; Scintillator Fiber Optic Long Counter for Neutron Detection; (U) 05/24/91. (UNCLASSIFIED)

240. Spencer, R.Smith, S.Smith, Humphries, Jones, Fitzgerald, Sharp, Pater; Fiber Optic Sensor System Assessment in Radiation Environments; (U) 10/17/94. (UNCLASSIFIED)

241. Tarabrin, Matevosov, Teplenichev; Fiber-optic and Television Endoscopes for Nuclear Power Engineering; (U) 10/17/94. (UNCLASSIFIED)

242. Taylor, Friebele, Henschel, West, Krinsky, Barnes; Interlaboratory Comparison of Radiation-Induced Attenuation in Optical Fibers. Part II: Steady State Exposures. (UNCLASSIFIED)

243. Taylor, Friebele, Krinsky, Johan, Henschel, Barnes, Looney, Dowling, McGovern; Report of the Nuclear Effects Task Group NATO Panel 4, Research Study Group .12; (U) 4/23/90. (UNCLASSIFIED)

244. Taylor, Padden, Sanchez, Chapman, Berry, DeWalt; Radiation-Induced Crosstalk in Guided Wave Devices; (U) 2/1/91. (UNCLASSIFIED)

245. Taylor, Sanchez, DeWalt, Craig, Chapman, Kelly, Mitcham; A Study of Radiation-Induced Effects in Photonic Devices: Acoustooptic Modulators and Deflectors - Preliminary Results; (U) 1994. (UNCLASSIFIED)

246. Taylor, Sanchez, DeWalt, Craig, Chapman; Electron Induced Responses in Acousto Optic and Spatial Light Modulators. (UNCLASSIFIED)

247. Taylor, Sanchez, DeWalt, Craig, Kelly, Chapman, Mitcham; Radiation Effects Observed in a Spatial Light Modulator. (UNCLASSIFIED)

248. Taylor, Sanchez, DeWalt, Padden, Chapman, Monarski, Craig, Page; Radiation Induced Effects in Acousto-Optic Devices. (UNCLASSIFIED)

249. Taylor, Sanchez, DeWalt, Padden, Chapman, Monarski, Craig, Page; Radiation Induced Effects in Acousto-optic Devices; (U) 8/10/92. (UNCLASSIFIED)

250. Taylor; Dual Use of Photonic Components in Radiation Environments. (UNCLASSIFIED)

251. Taylor; Germinate Recombination Behavior of a X-ray Irradiated Single-mode LiNbO3:Ti Waveguide Operating at 1300 nm; (U) 12/8/87. (UNCLASSIFIED)

252. Taylor; Intergrated Optic Response to Nuclear Irradiations; (U) 1/1/87. (UNCLASSIFIED)

253. Taylor; Ionization-induced Refractive Index and Polarization Effects in LiNbO3:Ti Directional Coupler Waveguides; (U) 8/10/90. (UNCLASSIFIED)

254. Taylor; On the Measurement of Radiation Induced Crosstalk in Polarization Preserving Optical Fibers and Directional Coupler Waveguides; (U) 7/3/91. (UNCLASSIFIED)

255. Taylor; Overview of Photonic Components for Space Applications: Radiation and Temperature Responses; (U) 4/13/93. (UNCLASSIFIED)

256. Taylor; Performance of the First Operable Fiber Optic Systems in Prolonged Space Orbit; (U) 2/14/92. (UNCLASSIFIED)

257. Taylor; Radiation Effects in Guided Wave Devices 8/12/92. (UNCLASSIFIED)

258. Taylor; Radiation Effects Observed in Selected Guided Wave Devices; (U) 1/21/93. (UNCLASSIFIED)

259. Thelen, Rankin, Marshall, LaBel, Krainak; Dual-rate MIL-STD-1773 Fiber Optic Transceiver for Satellite Applications; (U) 07/26/94. (UNCLASSIFIED)

260. Thompson, Lee, Passenheim; Experimental Evaluation of High Speed CCD Imager Radiation Effects Using Co60 and Proton Radiation. (UNCLASSIFIED)

261. Toossi, Modarress; Radiation and Temperature Survivability of Multimode Step-Index Fluorine-Doped Silica Fibers; (U) 10/91. (UNCLASSIFIED)

262. Utsumi, Hayami, Tanaka, Imai, Goho; Radiation Resistance of Pure-Silica Core Image Guides; (U) 8/22/84. (UNCLASSIFIED)

263. Watanabe, Matsui, Yokota, Isoya; The Reduction of the Radiation Induced Loss Increase of Pure Silica Core Single-Mode Fiber; (U) 1985. (UNCLASSIFIED)

264. Wei, Singh, Miniscalco, Wall; Effect of Hydrogen Treatment on Radiation Hardness of Optical Fibers; (U) 9/25/86. (UNCLASSIFIED)

265. Weiss; The Radiation Response of a Selfoc Microlens; (U) 2/16/90. (UNCLASSIFIED)

266. West, Buker, Friebele, Henschel, Lyons; The Use of Optical Time Domain Reflectometers to Measure Radiation-Induced Losses in Optical Fibers; (U) 04/94. (UNCLASSIFIED)

267. West, Dowling; Effects in a Lithium Tantalate Waveguide Structure Exposed to Radiation from a Flash X-Ray Source; (U) 9/13/93. (UNCLASSIFIED)

268. West, Dowling; Measurement of Long Term Radiation Induced Losses in Fiber Optics Using Optical Time Domain Reflectometry; (U) 9/9/91. (UNCLASSIFIED)

269. West, Dowling; The Effects of Ionizing Radiation and Hydrogen on Erbium Doped Fiber Amplifiers. (UNCLASSIFIED)

270. West, Lenham, Heathfield; Radiation Response of Fibre Optics at One Millisecond After Neutron or Gamma Irradiation; (U) 3/1/81. (UNCLASSIFIED)

271. West, Lenham, Heathfield; The Temperature Dependence of the Transient Radiation Response of Fiber Optics I; (U) 6/1/81. (UNCLASSIFIED)

272. West; Predicting the Response of Optical Fibers to Ionizing Radiation; (U) 10/17/94. (UNCLASSIFIED)

273. West; Radiation Induced Losses in Pure Silica Core Fibres; (U) 9/25/86. (UNCLASSIFIED)

274. Wiczer, Barnes, Dawson; Transient Effects of Ionizing Radiation in Si, InGaAsP, and Ge Photodiodes; (U) 3/25/80. (UNCLASSIFIED)

275. Wiczer, Barnes, Fischer; AlGaAs/GaAs Radiation Hardened Photodiodes; (U) 8/1/84. (UNCLASSIFIED)

276. Wiczer, Barnes; Optoelectronic Data Link Designed for Applications in a Radiation Environment; (U) 10/5/85. (UNCLASSIFIED)

277. Wiczer, Dawson, Osbourn, Barnes; Direct Bandgap, Ionizing-Radiation Insensitive, Photodiode Structures; (U) 8/25/81. (UNCLASSIFIED)

278. Wiczer, Dawson, Osbourn, Barnes; Permanent Damage Effects in Si and AlGaAs/GaAs Photodiodes; (U) 12/82. (UNCLASSIFIED)

279. Wiczer, Fischer, Dawson, Osbourn, Zipperian, Barnes; Pulsed Irradiation of Optimized, MBE Grown, AlGaAs/GaAs Radiation Hardened Photodiodes; (U) 12/4/84. (UNCLASSIFIED)

280. Wiczer; Radiation Response of a Radiation-Hardened Si Photodiode Incorporating a Sinker Diffusion; (U) 8/22/84. (UNCLASSIFIED)

281. Williams, Putnam, Askins, Gingerich, Friebele; Radiation-Induced Coloring of Erbium-doped Optical Fibers; (U) 12/31/92. (UNCLASSIFIED)

282. Williams, Putnam, Askins, Gingerich, Friebele; Radiation-induced Coloring of Erbium-doped Optical Fibers. (UNCLASSIFIED)

283. Zmuda, Pentrack, Bulcock, Greenwell, Lloyd; In-situ Measurement of the Effects of Neutron Irradiation on Polarization Maintaining Fibers; (U) 9/8/92. (UNCLASSIFIED)

284. Zucker, Clarke, Narciso; Transient Attenuation in Connectors to PCS Fibers and in Glass-on-Glass Fibers Induced by Pulsed X-Rays; (U) 8/22/84. (UNCLASSIFIED)

# APPENDIX B

# TEST PARAMETERS BY COMPONENT CLASS AND ENVIRONMENT

Test Parameters for Light Emitting Diode Under Total Dose

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.3 | 100 | 20 |
| Dose Amount [RAD(Si)] | 100 | 1.0E+09 | 1.0E+08 |
| Temperature (degrees C) | -150 | 160 | 25 |
| Operating Wavelength (nm) | 660 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -30 |
| Processing Speed (Mbps) | 0.078 | 4.0E+04 | 100 |

Test Parameters for Light Emitting Diode Under Prompt Transient

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.3 | 100 | 2.0E+04 |
| Dose Amount [RAD(Si)] | 100 | 1.0E+08 | 2.0E+04 |
| Temperature (degrees C) | -150 | 160 | 25 |
| Operating Wavelength (nm) | 660 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -30 |
| Processing Speed (Mbps) | 0.078 | 1000 | 100 |

Test Parameters for Light Emitting Diode Under Proton Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.3 | 20 | 20 |
| Dose Amount [RAD(Si)] | 2000 | 1.0E+08 | 1.0E+05 |
| Radiation Level (Protons/sqcm) | 1.0E+11 | 1.2E+15 | 1.0E+13 |
| Temperature (degrees C) | -150 | 160 | 25 |
| Operating Wavelength (nm) | 820 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -30 |
| Processing Speed (Mbps) | 0.078 | 1.0E+03 | 100 |

Test Parameters for Light Emitting Diode Under Neutron Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 3 | 500 | 20 |
| Dose Amount [RAD(Si)] | 100 | 5.0E+08 | 1.0E+08 |
| Radiation Level (Neutrons/sqcm) | 1.0E+08 | 7.8E+15 | 3.0E+14 |
| Temperature (degrees C) | -55 | 160 | 25 |
| Operating Wavelength (nm) | 660 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -30 |
| Processing Speed (Mbps) | 0.1 | 5.7E÷04 | 100 |

Test Parameters for Laser Diode Under Total Dose

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.3 | 3.5E+05 | 1.0E+05 |
| Dose Amount [RAD(Si)] | 100 | 1.0E+08 | 1.0E+06 |
| Temperature (degrees C) | -150 | 160 | 25 |
| Operating Wavelength (nm) | 660 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -30 |
| Processing Speed (Mbps) | 0.078 | 5.7E+04 | 100 |

Test Parameters for Laser Diode Under Prompt Transient

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.3 | 3.5E+05 | 2.0E+01 |
| Dose Amount [RAD(Si)] | 100 | 1.0E+08 | 1.0E+04 |
| Temperature (degrees C) | -150 | 160 | 25 |
| Operating Wavelength (nm) | 660 | 2000 | 1300 |
| Output Power (dBm) | -60 | 25 | -30 |
| Processing Speed (Mbps) | 0.078 | 1.0E÷03 | 100 |

Test Parameters for Laser Diode Under Proton Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.3 | 20 | 20 |
| Dose Amount [RAD(Si)] | 2.0E+03 | 1.0E+08 | 1.0E+05 |
| Radiation Level (Protons/sqcm) | 1.7E+11 | 2.0E+14 | 4.0E+11 |
| Temperature (degrees C) | -150 | 160 | 25 |
| Operating Wavelength (nm) | 820 | 2000 | 1300 |
| Output Power (dBm) | -60 | 21 | -30 |
| Processing Speed (Mbps) | 0.078 | 1000 | 100 |

Test Parameters for Laser Diode Under Neutron Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 3 | 3.5E+05 | 200 |
| Dose Amount [RAD(Si)] | 100 | 1.0E+08 | 1.0E+04 |
| Radiation Level (Neutrons/sqcm) | 5.0E+11 | 1.0E+15 | 4.0E+13 |
| Temperature (degrees C) | -67 | 160 | 25 |
| Operating Wavelength (nm) | 660 | 2000 | 1300 |
| Output Power (dBm) | -60 | 37 | -30 |
| Processing Speed (Mbps) | 10 | 5.7E÷04 | 100 |

Test Parameters for Coupler/Connector Under Total Dose

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 20 | 20 | 20 |
| Dose Amount [RAD(Si)] | 100 | 1.0E+09 | 3.0E+04 |
| Temperature (degrees C) | -65 | 220 | 25 |
| Operating Wavelength (nm) | 660 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -3 |
| Processing Speed (Mbps) | 10 | 2.0E+04 | 100 |

Test Parameters for Coupler/Connector Under Proton Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 20 | 20 | 20 |
| Dose Amount [RAD(Si)] | 40 | 4.4E+07 | 1.0E+05 |
| Radiation Level (Protons/sqcm) | 1.0E+11 | 1.0E+13 | 1.0E+11 |
| Temperature (degrees C) | -150 | 160 | 25 |
| Operating Wavelength (nm) | 663 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -20 |
| Processing Speed (Mbps) | 0.161 | 220 | 100 |

Test Parameters for Coupler/Connector Under Prompt Transient

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 3 | 5000 | 20 |
| Dose Amount [RAD(Si)] | 100 | 1.0E+09 | 3.0E+04 |
| Temperature (degrees C) | -55 | 220 | 25 |
| Operating Wavelength (nm) | 660 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -30 |
| Processing Speed (Mbps) | 20 | 200 | 100 |

Test Parameters for Coupler/Connector Under Neutron Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 20 | 20 | 20 |
| Dose Amount [RAD(Si)] | 100 | 1.0E+08 | 2.0E+04 |
| Radiation Level (Neutrons/sqcm) | 8.0E+11 | 1.2E+15 | 4.0E+14 |
| Temperature (degrees C) | -55 | 160 | 25 |
| Operating Wavelength (nm) | 660 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -3 |
| Processing Speed (Mbps) | 20 | 200 | 100 |

Test Parameters for IO Device/Modulator Under Total Dose

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 20 | 3.5E+05 | 1.0E+04 |
| Dose Amount [RAD(Si)] | 18 | 1.0E+09 | 2.0E+05 |
| Temperature (degrees C) | -55 | 220 | 25 |
| Operating Wavelength (nm) | 350 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -30 |
| Processing Speed (Mbps) | 20 | 2.0E+04 | 100 |

Test Parameters for IO Device/Modulator Under Prompt Transient

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 3 | 3.5E+05 | 1000 |
| Dose Amount [RAD(Si)] | 100 | 1.0E+09 | 3.0E+05 |
| Temperature (degrees C) | -55 | 220 | 25 |
| Operating Wavelength (nm) | 350 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -12 |
| Processing Speed (Mbps) | 20 | 200 | 100 |

Test Parameters for IO Device/Modulator Under Proton Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 20 | 20 | 20 |
| Dose Amount [RAD(Si)] | 2.0E+03 | 1.0E+08 | 3.0E+04 |
| Radiation Level (Protons/sqcm) | 1.0E+13 | 1.0E+13 | 1.0E+13 |
| Temperature (degrees C) | -55 | 160 | 25 |
| Operating Wavelength (nm) | 820 | 2000 | 850 |
| Output Power (dBm) | -60 | 20 | -30 |
| Processing Speed (Mbps) | 0.161 | 200 | 100 |

Test Parameters for IO Device/Modulator Under Neutron Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 20 | 3.5E+05 | 8.0E+04 |
| Dose Amount [RAD(Si)] | 2.0E+03 | 1.0E+08 | 3.0E+04 |
| Radiation Level (Neutrons/sqcm) | 8.0E+12 | 1.2E+15 | 2.0E+13 |
| Temperature (degrees C) | -55 | 160 | 25 |
| Operating Wavelength (nm) | 820 | 2000 | 1050 |
| Output Power (dBm) | -60 | 20 | -40 |
| Processing Speed (Mbps) | 20 | 200 | 100 |

Test Parameters for Optical Fiber Under Total Dose

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.5 | 1.0E+06 | 1.0E+05 |
| Dose Amount [RAD(Si)] | 2.9 | 2.6E+09 | 3.5E+03 |
| Temperature (degrees C) | -173 | 320 | 25 |
| Operating Wavelength (nm) | 210 | 4000 | 850 |
| Output Power (dBm) | -60 | 43 | -30 |
| Processing Speed (Mbps) | 0.078 | 5.7E+04 | 100 |

Test Parameters for Optical Fiber Under Prompt Transient

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.3 | 2.0E+07 | 30 |
| Dose Amount [RAD(Si)] | 2.9 | 1.5E+08 | 2.0E+04 |
| Temperature (degrees C) | -193 | 210 | 25 |
| Operating Wavelength (nm) | 210 | 2030 | 850 |
| Output Power (dBm) | -60 | 53 | -30 |
| Processing Speed (Mbps) | 0.078 | 1000 | 100 |

Test Parameters for Optical Fiber Under Proton Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.3 | 20 | 20 |
| Dose Amount [RAD(Si)] | 40 | 1.0E+08 | 3.0E+05 |
| Radiation Level (Protons/sqcm) | 1.0E+06 | 1.0E+13 | 1.0E+11 |
| Temperature (degrees C) | -55 | 160 | 25 |
| Operating Wavelength (nm) | 560 | 2000 | 1300 |
| Output Power (dBm) | -60 | 21 | -30 |
| Processing Speed (Mbps) | 0.078 | 1000 | 250 |

Test Parameters for Optical Fiber Under Neutron Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 3 | 2.5E+12 | 1.0E+05 |
| Dose Amount [RAD(Si)] | 400 | 2.6E+09 | 2.0E+05 |
| Radiation Level (Neutrons/sqcm) | 1.0E+08 | 2.0E+20 | 3.0E+14 |
| Temperature (degrees C) | -55 | 200 | 25 |
| Operating Wavelength (nm) | 190 | 2030 | 850 |
| Output Power (dBm) | -60 | 53 | -30 |
| Processing Speed (Mbps) | 0.1 | 5.7E+04 | 100 |

Test Parameters for Photodiode/Detector Under Total Dose

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.3 | 3.5E+05 | 1.0E+05 |
| Dose Amount [RAD(Si)] | 300 | 1.0E+09 | 1.0E+06 |
| Temperature (degrees C) | -150 | 160 | 25 |
| Operating Wavelength (nm) | 660 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -30 |
| Processing Speed (Mbps) | 0.078 | 5.7E+04 | 400 |

Test Parameters for Photodiode/Detector Under Prompt Transient

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.3 | 3.5E+05 | 50 |
| Dose Amount [RAD(Si)] | 100 | 1.0E+08 | 1.0E+05 |
| Temperature (degrees C) | -150 | 160 | 25 |
| Operating Wavelength (nm) | 650 | 2000 | 1300 |
| Output Power (dBm) | -60 | 20 | -23 |
| Processing Speed (Mbps) | 0.078 | 1.0E+03 | 100 |

Test Parameters for Photodiode/Detector Under Proton Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 1.3 | 20 | 1.3 |
| Dose Amount [RAD(Si)] | 40 | 1.0E+08 | 1.0E+05 |
| Radiation Level (Protons/sqcm) | 2.0E+05 | 1.0E+13 | 1.0E+11 |
| Temperature (degrees C) | -150 | 160 | 25 |
| Operating Wavelength (nm) | 820 | 2000 | 1300 |
| Output Power (dBm) | -60 | 21 | -30 |
| Processing Speed (Mbps) | 0.078 | 1.0E+03 | 400 |

Test Parameters for Photodiode/Detector Under Neutron Fluence

| Parameter | Minimum Value | Maximum Value | Typical Value |
|---|---|---|---|
| Duration (ns) | 3 | 3.5E+05 | 20 |
| Dose Amount [RAD(Si)] | 300 | 5.0E+08 | 1.0E+08 |
| Radiation Level (Neutrons/sqcm) | 1.0E+11 | 3.6E+15 | 4.0E+14 |
| Temperature (degrees C) | -55 | 160 | 25 |
| Operating Wavelength (nm) | 650 | 2000 | 850 |
| Output Power (dBm) | -60 | 20 | -30 |
| Processing Speed (Mbps) | 0.1 | 5.7E+04 | 100 |

# APPENDIX C

# PHOTONICS ACRONYMS

| | |
|---|---|
| AFMC | Air Force Material Command |
| AO | Acousto-optic |
| APD | Avalanche photodetector |
| CCD | Charge Coupled Devices |
| EDFA | Erbium doped fiber amplifiers |
| EO | Electro-optic |
| ERS | Earth Resources Satellite |
| ESR | Electron spin resonance |
| FLC | Ferroelectric Liquid Crystal |
| GEO | Geosynchronous Orbit |
| GPS | Global Positioning Satellite |
| HBT | Heterojunction Bipolar Transistor |
| HEMT | High Electron Mobility Transistor |
| IO | Integrated Optics (structures) |
| LC | Liquid Crystal |
| LCLV | Liquid Crystal Light Valve |
| LCTV | Liquid Crystal Television |
| LD | Laser Diode |
| LED | Light emitting diode |
| LEO | Low Earth Orbit |
| MO | Magneto-Optic |
| MQW | Multiple Quantum Well |
| MSLM | Microchannel SLM |
| NETG | Nuclear Effects Task Group |
| PCS | Polymer Clad Silica |
| PGP | Photoline Gel Polymer |
| PMMA | Poly-methyl Methacrylate |
| PT | Prompt Transient |
| QCSE | Quantum Confined Stark Effect |
| RHA | Radiation Hardness Assurance |
| SAW | Surface Acoustic Wave |
| SHG | Second Harmonic Generation |
| SLM | Spatial Light Modulators |
| TD | Total Dose |

| | |
|---|---|
| TID | Total Ionizing Dose |
| T-SEED | Transistors-Self Electro-Optic Effect Device |
| VLSI | Very Large Scale Integration |
| WDM | Wavelength Division Multiplexed |

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